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A METHODOLOGY FOR ASSESSING TECHNOLOGY TRADE-OFFS OF SPACE-BASED RADAR CONCEPTS

THESIS

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THESIS

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Preface

This study outlines a methodology to compare potential military space systems. The methodology presented takes advantage of the corporate knowledge contained in the Military Space Systems Technology Plan (MSSTP) to provide an integrated approach for making space system trade-offs. The approach attempts to show how to bring together the vast amount of technical data and the necessary expert opinion to formulate a decision.

Space-based radar design options serve as the vehicle for demonstrating this methodology. Such an approach serves as an appropriate means to link Air Force planning functions with operational missions and the technologies that support those missions. In this way, the methodology provides a necessary insight on how to deal with space system technologies from the MSSTP perspective. It is my hope that this effort will help clarify the multiple issues facing the military decision maker when planning for future space systems.

I would especially like to thank my thesis advisor, Lt Col Mark Mekaru of the Air Force Institute of Technology, for his professional insight and expert guidance. His willingness to provide assistance on a daily basis made this effort possible. I would also like to acknowledge the Air Force Space Technology Center for their sponsorship. I

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Finally, I wish to express my heartfelt thanks to my wife, Diana. She provided the patience, understanding, and support that were so important to my efforts.

John Puffenbarger

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Abstract

A methodology is developed to aid a decision maker in assessing the technology trade-offs for space system concepts. A review of systems engineering and the tools of operations research shows that the analytic hierarchy process provides a suitable basis for this methodology.

The possible concept options that fall under the overall space-based radar concept are representative of the multiple trade-offs inherent in planning for future space systems. Many of the technology issues appropriate to space-based radar concepts are presented to establish a foundation for the methodology.

The proposed methodology exposes the three phases of the analytic hierarchy process and how they interact to provide an overall priority for a selected number of concept options. Particular emphasis is placed on the division of the decision process according to a decision hierarchy and a support hierarchy. A key feature of such an approach is its compatibility with the format and terminology of the Military Space Systems Technology Plan developed by the Air Force Space Technology Center.

Three concept options serve as representative systems to demonstrate the feasibility of the methodology. Recommendations on how to expand upon the model follow this example. Concluding remarks suggest a decision support

system based on this methodology using the AFSTC Data Base Management System to enhance the MSSTP decision process.

A METHODOLOGY FOR ASSESSING TECHNOLOGY TRADE-OFFS OF SPACE-BASED RADAR CONCEPTS

I. INTRODUCTION

BACKGROUND

In recent years, the Air Force has stressed space technology developments as a means for meeting national defense objectives. President Reagan emphasized this aspect of US policy during a speech in July 1982. He directly linked national security to space programs (19:23). Because of this relationship, the Department of Defense has initiated several technology reviews. The purpose of these studies is to define and compare the technological requirements for employing space-based systems in a military role (17:66; 22; 23:40). The Strategic Defense Initiative (SDI) and the Space Systems Architecture Study (SSAS) are two such reviews involving the Air Force (1:21; 19:29). Identifying the technological needs for future space systems through these and similar reviews presents a significant challenge.

A broad range of technological information applicable to space systems has been consolidated to enhance the review process. To be comprehensive, reviews must address an extensive and diversified range of technological problems.

The Air Force recognizes the need to develop and maintain a technical data base to cover this range of space research and development issues. The Air Force Space Technology Center (AFSTC) currently manages a technical data base of space technologies important to space studies (44; 45). AFSTC has established that the ordering of the data is also essential (28:3-21). The document that AFSTC uses in ordering technical data to better integrate space planning with the associated technologies is the Military Space Systems Technology Plan (MSSTP).

The MSSTP provides a structure for analyzing US capability to develop military space systems based on the present and projected status of our technology. The MSSTP achieves this ordering by categorizing space systems in a hierarchical fashion. The fundamental element within this MSSTP conceptual framework is the technology issue. A technology issue is a technology whose estimated state of the art at some future point fails to meet the projected level required of that technology by a particular space system (28:3-38). Several technology issues within a single scientific discipline comprise a technology discipline. The space system concept is, in turn, composed of selected technology disciplines. A concept is a general type of space system that accomplishes a specific mission (26a:v). Figure 1 depicts the fundamental relationship represented through this terminology.

Concept
|
Technology Disciplines
|
Technology Issues

Figure 1. MSSTP Fundamental Structure (26a:iv)

The MSSTP, therefore, provides a network of technology disciplines and technology issues to characterize space system concepts. Not all technology disciplines may be relevant to a particular space system concept. Likewise, not all technology issues under a single discipline necessarily apply to all concepts. By relating only the applicable technology disciplines to a specific concept, the MSSTP's hierarchical structure links appropriate technology issues with the corresponding space system concepts.

Although the MSSTP provides a structure, the MSSTP does not provide a well-defined methodology to choose between alternative concept options. Concept option, in this context, means one of several specific space system designs that will accomplish the mission outlined by a space system concept. For example, the planar station and tower station designs are two concept options in deploying the space station, a NASA space system concept (14:15). Choosing among

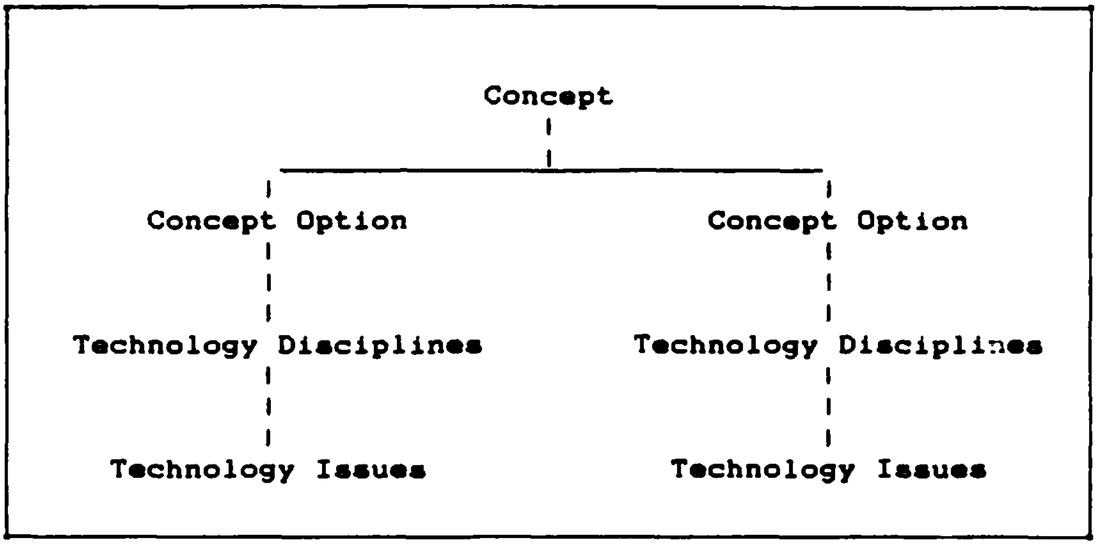


Figure 2. Concept Options within the MSSTP

concept options becomes difficult without a workable methodology upon which to base decisions. The methodologies that have been studied for the MSSTP concentrate primarily on the overall structure of the plan itself (28:1-3). A methodology that allows the decision maker to choose a concept option based on the characteristics of inherent technology issues would provide more utility. Figure 2 depicts this relationship given by the additional consideration of the concept option in the MSSTP structure. Presently, no methodology has been demonstrated for accomplishing a trade-off analysis of a proposed technology concept (41).

The space-based radar is one technology concept of particular interest to the Air Force. In 1984, the Commander of Air Force Systems Command directed AFSTC to con-

duct a study of technology concept options for space-based radar (40). AFSTC relied upon the MSSTP, a special working group, and other Air Force agencies in conducting the review (40). For lack of a comprehensive method for analyzing the interrelationships between issues, the study analyzed each option independent of the others. Technologists identified common issues but did not have a methodology to compare attributes at the technology issue level (41).

An appropriate methodology based on the MSSTP structure would enhance decisions on space-based radar concept options. There exist a number of technology disciplines particular to a space-based radar concept option. While the MSSTP specifies a unique set of technology issues associated with each technology discipline, the MSSTP does not specify which technology issues are applicable to a particular space-based radar design. Many technology issues that impact the decision are not apparent. Those technology issues that are apparent are too numerous to compare without an appropriate methodology (41).

The additional attributes of schedule, cost, and risk also enter into the decision process (26h:4-2). Even though the values of these attributes are often subjective when based on future needs, techniques are available to enter them into the decision process as reasonable evaluators of performance (28:2-28). Fortunately, the MSSTP includes these measures to a degree even though no apparent internal methodology uses them to the extent they could be used to

evaluate space systems. By associating these subjective attributes with the technology issues, it is possible to demonstrate a methodology that allows decision makers to better choose between concept options. The space-based radar concept serves as a representative test case for implementing this methodology.

RESEARCH PROBLEM

The MSSTP methodology is incomplete. In its present form, the methodology fails to capitalize on the MSSTP's full potential to support the decision maker. Technology issues are not related to technology concepts through a methodology that fosters clear trade-offs between concept options. In particular, decision makers are unsure of how to compare different space-based radar options within the context of the MSSTP structure. The numerous technology issues inherent in space-based radar designs have not been structured through a methodology that provides for a trade-off analysis of concept options.

A question emerges based on these observations and the considerations mentioned in the background discussion. By considering technology issues within the structure of the Military Space Systems Technology Plan, how may a methodology be developed to analyze technology trade-offs in selecting a space-based radar?

Two specific areas are of particular concern in

answering this question and developing an analysis for space-based radar options. One problem to overcome is providing a solution through a methodology that parallels the MSSTP structure. The methodology must be flexible enough to allow decision makers to apply the same technique to other MSSTP related space systems. If this can be achieved, the approach has a more universal application to concepts other than just space-based radar. The methodology, then, also benefits from the wide circulation of the MSSTP, thus capitalizing on the availability of technological data that is in a usable format.

An additional problem arises due to the futuristic nature of the topic. Projecting future capabilities introduces a degree of uncertainty to the problem. Judgment based on experience is, therefore, an essential ingredient. The methodology for presenting the space-based radar analysis must make appropriate use of predictions and do so from the MSSTP perspective.

PURPOSE AND SCOPE

The methodology presented here provides the structure and the analytical tools to assist a space systems manager in decision making. The proposed methodology integrates the substantial technical data on space systems from the MSSTP data base with the complex decision environment of operational military forces. This approach incorporates

the elements of performance, cost, schedule, and risk to analyze concept options. The universal appeal of these elements to all space systems reinforces the idea that the application of this methodology extends beyond just space-based radar. Any concept with its associated concept options could be subjected to a similar analysis.

The proposed methodology also suggests to the systems analysts a way to incorporate the MSSTP in the decision process. The approach depicts the MSSTP as an initial input to an expanding process that improves a decision maker's understanding of technology issues through each iteration.

The space-based radar options presented in this work represent actual point designs only for the sake of exercising the methodology. The intent here is to detail and demonstrate the methodology, not to actually recommend selections between potential radar designs. The engineering effort to achieve the latter far exceeds the scope of this work.

APPROACH

Multicriteria decision theory appears well suited to accomplishing a trade-off analysis for space-based radar options. Taken independently, single attributes of technology issues may not adequately model the alternatives for the decision maker (51:1-2). Multiple criteria analysis,

however, incorporates the complexity and diversity of attributes into a relationship that emphasizes their interdependence (11:4-5). For space-based radar, such an approach is desirable due to the numerous technology issues that affect design or performance. Most parameters cannot be linked directly for comparison. This diversity of the input parameters seems particularly well suited to multiple criteria analysis within the MSSTP framework.

The input parameters for a model appropriate to a space-based radar trade-off analysis are of two classifications. The first group consists of those parameters that are subjective by nature. These input variables represent measures such as the potential risks or costs often associated with developing future technologies. Being subjective, they exhibit variability in what can be considered reasonable estimations. Their values can be determined in several ways. One manner is by value assessments from a group of technologists who are experts in the particular discipline in question (21:26). The second group of parameters is specified by engineering design. As such, the associated parameters have a range of values bounded by the physical limitations of science or operational necessity. Chankong and Haimes refer to these parameters as "factual elements" (11:6). Although variable to a degree, they are bounded and can typically be quantified given the applicable constraints.

In the case of space-based radar, employing a multiple

criteria based methodology can provide the means for interrelating subjective and engineering limited types of input parameters. The relationship between input parameters and the technology issues facilitates this approach. The input parameters are essentially the attributes of the technology issues. By identifying all of the technology issues under a specific option, the associated attributes are available for comparison. From that point, quantitative attributes can be traded off directly. Subjective attributes, on the other hand, can be grouped into common categories suitable for trade-off computations. Finally, relative weights can be assigned and a comparison made across all attribute categories of the different space-based radar options.

The nature of the individual attributes that characterize the technology issues supports the analytic hierarchy process as an appropriate multicriteria technique for space systems. The mix of subjective and scientifically quantifiable attributes demands flexibility. The analytic hierarchy process (AHP) promises to provide this flexibility. This approach presents the relative weights of judgment criteria that arise from value assessments in a structured manner for the decision maker. Comparisons can be made with relative ease under this structured decision process. Justification for selecting one option over another is readily displayed through AHP's definitive hierarchy. Furthermore, since the intent of the methodology is to capture the complexities of the problem without modeling the

decision maker, AHP allows for necessary revisions in a dynamic policy environment. Thus, the overall methodology benefits from AHP's more universal application.

An initial data base to support this approach already exists. The Space Technology Center (STC) has extensive information on technology issues that can aid in assigning values to attributes of space technology issues (28:3-21). The STC has offered support in making this data available and continues to expand their capability to provide future technology characterization (41). Furthermore, steering groups organized by STC have consolidated considerable subjective data on space-based radar through survey (40). In addition, the MSSTP also provides substantial background on related technology issues that impact on space-based radar parameters. Collectively, these sources provide the necessary input data to describe technology issues used to demonstrate the methodology for space-based radar.

OVERVIEW

Chapter 2 begins by discussing the key elements of the decision environment. In particular, the presentation emphasizes the qualities that are beneficial to an effective methodology. The discussion then identifies systems engineering and the analytic hierarchy process, in turn, as a conceptual framework and an analytical tool that complement one another. Both tie in well with the objectives that a

model must encompass and offer motivation for the methodology that follows.

Having expanded the theoretical background in Chapter 2, Chapter 3 covers pertinent technical considerations specific to space-based radar. The basic radar equation and associated parameters are presented. The review stresses some of the important trade-offs that complicate design selections as well as the unique terminology needed to define space-based radar systems. The chapter attempts to familiarize the reader with those space-based radar issues necessary to follow the example presented later on in the paper.

Chapter 4 details the methodology for assessing trade-offs of space-based radar concepts. All three phases of the analytic hierarchy process are discussed in the context of space-based radar. This chapter introduces the dual nature of the space-based radar hierarchy by explaining the separate decision and support hierarchies fundamental to the methodology's structure.

Chapter 5 implements the methodology by considering three space-based radar concept options. Calculations through this example further demonstrate how to exercise the methodology to evaluate the candidate systems. The example prioritizes the candidate space-based radar options based on value assessments and pairwise comparison solicited through survey from a panel of technologists.

Finally, Chapter 6 suggests some benefits of framing

problems in the format of the proposed methodology. Recommendations are provided on how to enhance the value of this formulation through real-time computer data base management support. This final chapter concludes by providing some suggestions for further research using this methodology as a point of departure.

II. Perspectives on Space Systems Planning in a Complex Decision Environment

Introduction

As Air Force interests turn toward employing space assets in more operational roles, effectively planning for future systems becomes increasingly complex. Along with deploying operational space assets in support of DOD missions comes the added requirement to more thoroughly review alternative concepts for optimum mission performance. This need becomes critical when one considers the enormous material and manpower resources required to orbit a space system.

Space systems possess unique complexities not found in even some of the most advanced terrestrial systems. The environment in which space systems function requires designers of these systems to solicit inputs from a diverse range of scientific disciplines. This requirement places extraordinary demands on decision makers who become involved in judging space systems for their ability to fulfill mission objectives.

Space-based radar is representative of the type of complex space system that is plagued with integration problems for the military manager. As such, space-based radar serves as an appropriate subject upon which to demonstrate a methodology for analyzing complex space systems. Such an

analytical methodology provides the tools to allow the decision maker to make the technological assessments required to comprehend the engineering and design trade-offs. This, in turn, leads to a more well-founded system selection.

The background literature applicable to making technological assessments of space-based radar is of two general types. First, there is a wealth of decision theory that provides a background on techniques used to evaluate issues against one another in terms of overall objectives. This theoretical aspect provides the means to formulate order from the unstructured problem. Secondly, there exists material addressing the technological base from which a proposed system must evolve. These facts expose the physics issues and provide substance to the problem. The methodology presented here suggests a mechanism by which the technical data can be manipulated in an ordered fashion through decision theory so that a methodology exists to support the decision maker. With this goal in mind, this chapter analyzes the theoretical aspects of solving large-scale problems while Chapter 3 details the technical concerns of space-based radar.

The Decision Environment

Choosing between alternative methodologies for assessing trade-offs in large-scale systems complicates the decision process. Especially in the environment of

technologically sophisticated systems, decision making is both complex and varied. The method for making these systems related decisions takes many forms. Selecting an appropriate technique to arrive at a decision for a specific system presents a challenge to most organizations. By having a grasp of available methodologies, an analyst enhances the ability to frame problems in a manner that will better expose interrelationships and dependencies between elements. A review of an approach that has a potential application to resolving planning trade-offs similar in nature to those for space-based radar, thus, serves to lay a solid foundation for this study.

Although several methodologies exist for multicriteria decision making, some methods appear more appropriate in dealing with the uniqueness of the military research and development environment. The characteristics of systems engineering coupled with the analytical tools of operations research appear to be readily applicable to the issue of making space-based radar trade-off studies. Narrowing the scope of this research does not imply that other methods would be inappropriate. On the contrary, other methods might easily be incorporated into the analysis presented here, particularly in the area of value assessments. A review of the available literature provides valuable insight into why a combination of systems engineering with the analytical tools of operations research are applicable to space-based radar decisions.

System Complexity. Foremost in selecting a methodology for dealing with space-based radar issues is the ability to process multiple concerns. Several authors stress the importance of capturing the multifaceted aspect of relationships in complex systems (21:66-67; 25:261-265; 30:4; 33:499-500; 34:91-92; 43:7; 48:390). De Neufville and Stafford relate:

> [Models] must not only describe the interactions between the complex factors of the environment which will load the system, but must also identify the casual dependencies between these factors, so that the analyst can correctly perceive the effect of the substantial changes that may be introduced by a large-scale project [16:4].

Decision making has had to evolve to keep pace with the complex systems of our increasingly technologically oriented society. Souder points out the distinction between traditional decision making and today's more technical decision making process:

> Engineers and scientists must be able to integrate human and nonhuman considerations into their decisions. Modern technical decision making involves a sensitivity to organizations, institutions, people and society as well as technology. Thus, modern day engineers and scientists have a substantial need to rely on the structured decision making process [43:7].

Souder's view reflects the concern that the increasing level of complexity in today's problems must be dealt with if effective choices are to be made between alternatives.

Two facets of complexity are dominant concerns for decision makers when evaluating space systems. One of these complexities, referred to here as complexity of type, is

caused by the interdisciplinary nature of the space system itself. Complexity of type is borne out of the requirement to search outside of one's own area of expertise to solve problems. The need to match real world constraints with a system's intended purpose drives this requirement. Complexity of type manifests itself as an integration problem which includes all of the social, economic, political, and technological concerns voiced by proponents within each discipline.

The other facet of complexity facing space systems decision makers is brought about by the sheer abundance and uncertainty of information. Referred to here as complexity of quantity, this aspect of complexity stems from the large number of alterables within a very wide range of uncertain constraints. That is to say, there is so much information available that the decision maker is unable to sort out what information of a particular discipline is really relevant to the problem at hand.

In a sense, the decision maker can deal with complexity of type and complexity of quantity in two slightly different ways. Defining a structure to specify interrelationships among disciplines limits complexity of type. Structuring tells the decision maker how to interpret interrelationships by diagramming the linkages between disciplines. In a complementary manner, correctly scoping the problem to program needs within a single discipline limits complexity of quantity. Making assumptions based on

experience and judgment can specify a starting point to scope the problem for subsequent iterations. Both of these methods for dealing with complexity present a considerable challenge, but greatly enhance a decision maker's understanding of a complex system such as space-based radar.

Structure. Assigning structure to a problem provides a means to simplify decision making. Souder relates:

> the further away we get from the well-ordered world of technical decision making and the closer we get to the less-structured world of managerial decision making, the more important it becomes to use the structured decision process [43:8].

Problem solving is often viewed as an art. Nevertheless, it is still our ability to apply logic to a complex situation. The human mind, however, can only assimilate a limited number of dissimilar items without becoming burdened with seemingly unrelated facts (15:244, 256). There are techniques for overcoming this barrier. Saaty provides some insight as to how to attack this problem:

> We need instead to organize our problems in complex structures which allow interactions and interdependence of factors but which also allow us to think about them one or two at a time [32:140].

Saaty advocates the analytic hierarchy process (AHP) as an effective means of structuring problems in a manner that is conducive to an analytical solution. Sage's systems engineering approach is more global, but recognizes the value of structure in optimizing trade-offs (34:91). Unfortunately, when dealing with large-scale systems, the decision maker is often more than one individual. While a single

decision maker may view needs from one perspective, multiple interests compete when a collective judgment is required. Additional considerations then contribute to reaching a consensus.

Group Interaction. In a large-scale system, the influence of several agencies bears upon the solution to the problem. Group consensus is important to the overall process. Saaty argues:

> AHP facilitates this meeting of the minds by imposing a discipline on the group's thought processes. The necessity of assigning a numerical value to each variable of the problem helps decision makers to maintain cohesive thought patterns and to reach a conclusion. In addition, the consensual nature of group decision making improves the consistency of the judgments and enhances the reliability of the AHP decision making tool [30:5].

Keeney and Raiffa prefer to think of the individual as the synthesizer of group concerns, with the prime purpose of the group being to structure the decision maker's preferences (21:516). Their group process helps to define the decision maker's preference structure to aid the decision maker in choosing between alternatives (21:520). In general, group interaction expands upon the decision maker's ability to recognize the problem.

Communication. Communicating design problems between experts of separate disciplines is another key issue in decision making. To communicate the nuances of technology and relative importance to overall performance of alternative technologies presents a challenge. Sage explains, "Lack of understanding of the structure of the

underlying system often leads us to the wrong conclusion regarding problem solution" (34:2). De Neufville and Stafford highlight the need "to challenge loosely stated goals defined by clients or professionals from other fields and thus to identify the fundamental purpose of a system" (16:7). The manner in which one arrives at a decision normally demands justification. A methodology that communicates problem complexities through effective structure and group interactions supplies this justification. To be even more effective, change must be taken into account.

Flexibility. In dealing with a future system, it is especially important to implement planning with a methodology that allows for change. This sensitivity to change with time is characteristic of AHP:

> The AHP is flexible enough to allow revision--decision makers can both expand the elements of a problem hierarchy and change their judgments. It also permits them to investigate the sensitivity of the outcome to whatever kinds of change may be anticipated. Each iteration is like hypothesis testing; the progressive refinement of hypotheses leads to a better understanding of the system [30:22].

Other authors often refer to the feedback process when stressing the need to incorporate flexibility in decision methodologies. De Neufville and Stafford explain the necessity of this feature:

> Since the time required to implement a large-scale project is usually both long and full of uncertainties, the initial analysis results in only a preliminary approximation to the design desirable at the end. It is therefore necessary to refine the plan as the project is installed and as uncertainties are resolved [16:14].

With a flexible methodology, major design alterations only cause minor conceptual rearrangements, thereby illuminating the new alternatives for the decision maker.

Decision makers could benefit greatly from a methodology that incorporates all the elements of the complex decision environment. Each is tied to the other and contributes to a more effective overall problem solution. Seldom is a decision methodology successful without having taken into account the elements of complexity, structure, group synthesis, communication and flexibility.

Systems Engineering

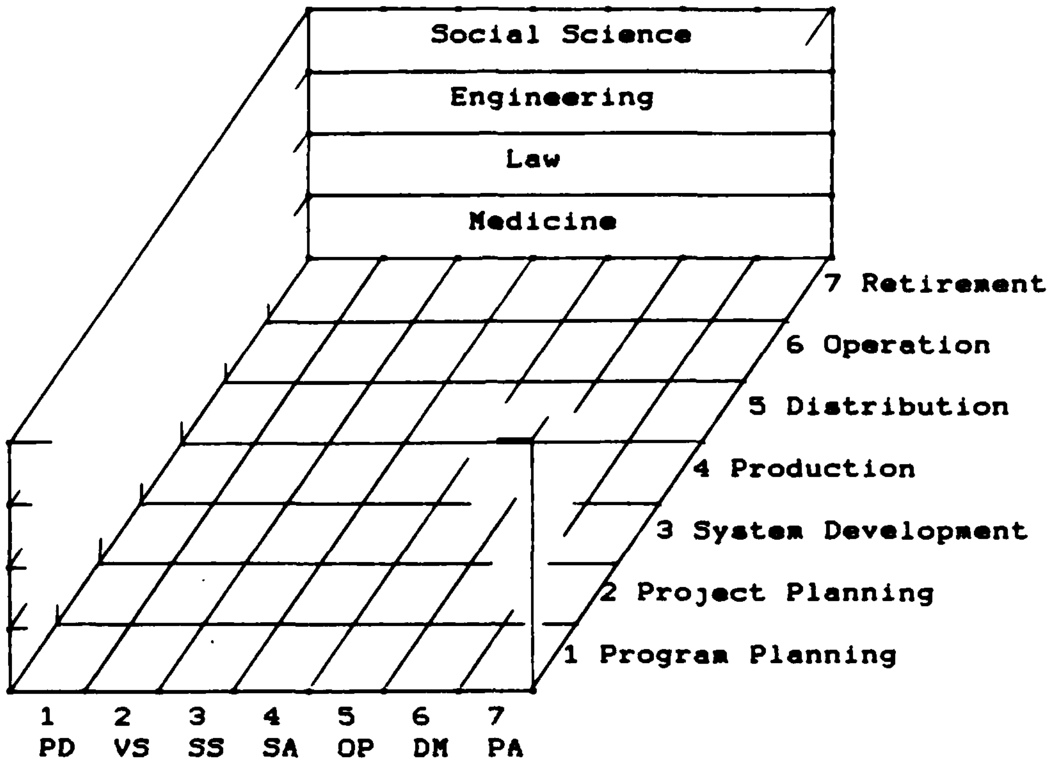
The methodology for making decisions on large-scale systems must address the issues inherent in the decision environment. Systems engineering is one approach that provides such a perspective. The central theme of systems engineering captures the needs of the decision environment. In addition, systems engineering tools are well-tailored to large-scale systems. All elements of the decision environment previously mentioned are inherent in the framework provided by systems engineering.

Systems engineering is particularly well-suited to systems integration problems. Emphasis is on subsystem contributions to overall performance. Morton's portrayal of systems engineering provides the following insight on the functional relationships:

> The Systems Engineering method recognizes each system is an integrated whole even though composed of diverse, specialized structures and subfunctions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and to achieve maximum compatibility of its parts [12:8].

Techniques from systems engineering are readily applicable to space-based radar problem solving. In particular, one can identify which phase of systems engineering characterizes the current state of space-based radar concerns. Hall's morphological box illustrates the evolutionary process of systems engineering pictorially as shown in Figure 3 (34:4). From this perspective, one can designate current space-based radar activity as falling in the program planning phase. Within this one phase, the decision makers progress through the seven steps of systems engineering. Of particular concern is the step of optimizing alternatives. It is in this step that the tools of operational science support the decision maker. In essence, this whole structure of systems engineering thus provides the initial framework required to begin dealing with trade-offs. Amplification of the associated techniques is in order to further show the merits of this approach.

<u>Analytical Sequence</u>. The process of systems engineering adheres to the principles of systematic scientific development. De Neufville and Stafford suggest a five element sequence for problem solving using the systems



Steps of Systems Engineering

PD = Problem Definition
VS = Value System Design
SS = System Synthesis
SA = System Analysis
OP = Optimization
DM = Decision Making
PA = Planning for Action

Figure 3. Hall's Morphological Box (34:4)

engineering approach (16:6):

1. Definition of objectives

2. Formulation of measures of effectiveness

3. Generation of alternatives

4. Evaluation of alternatives

5. Selection

Rather than divide systems engineering into a sequence of events, Chestnut chooses to identify five precepts for systems engineering. He agrees with De Neufville and Stafford in recognizing the need for an acceptable standard upon which to make value judgments of a system (12:11).

Criteria. Weighting functions provide the means to compare relative values in systems engineering. The weighting function adds flexibility. Weighting tacitly recognizes that overall system performance does not depend on each individual subsystem achieving its maximum objective. Because the nature of the weighting function is not easily expressed, seeking these values is an important outcome of this methodology.

Values must be assigned to a system based on some specified criteria. Generally, the criteria stem from the needs and objectives associated with the system. Chestnut, however, identifies five commonly accepted standards (12:11):

1. Performance
2. Cost
3. Time
4. Reliability
5. Maintainability

This list is subject to change based upon what the decision maker feels is an issue. For example, reliability and

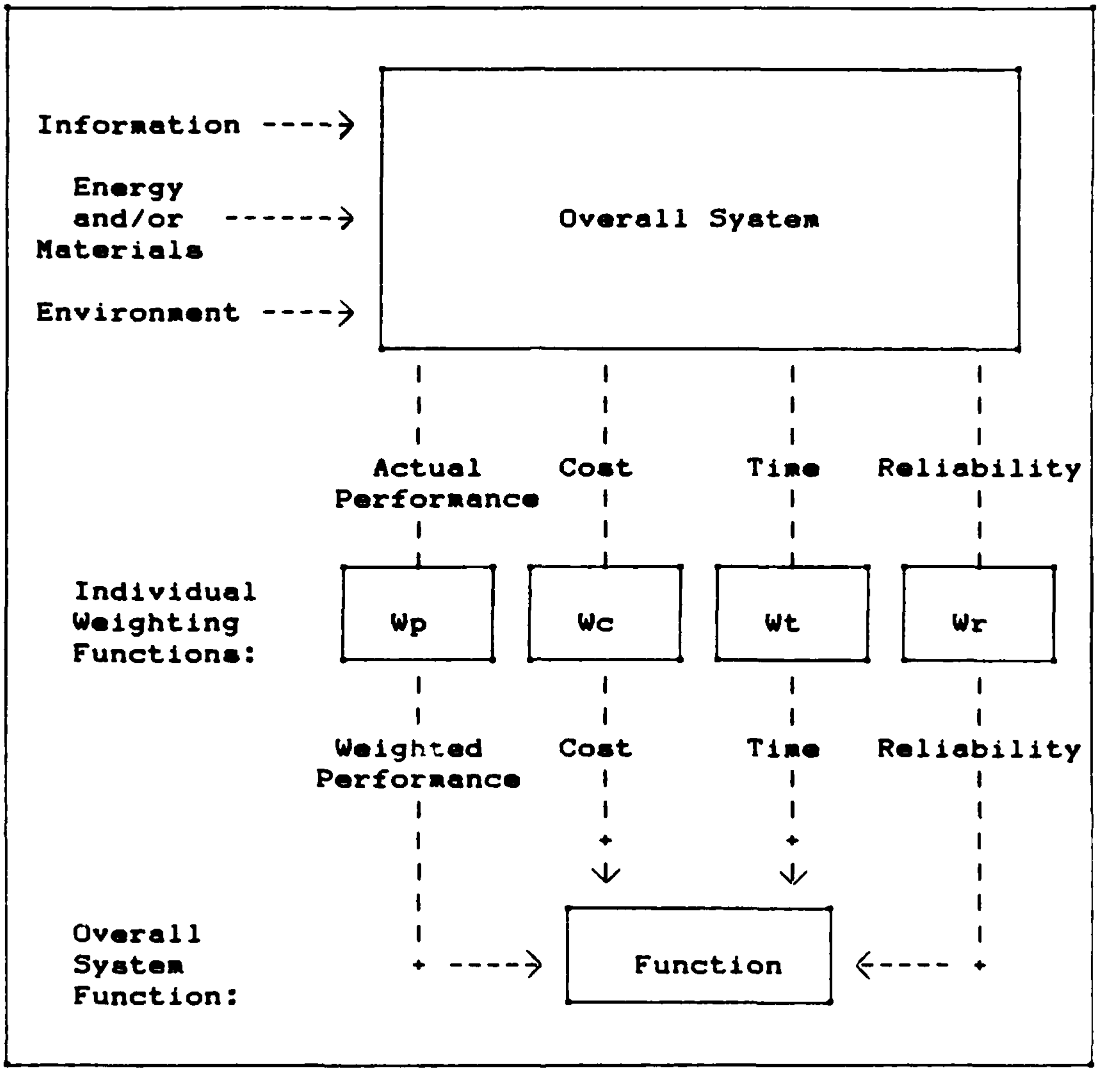


Figure 4. Weighted Contributions to System Worth (12:10)

maintainability might be included as a subset of performance. On the other hand, the military may be justified in levying additional standards based upon the unique requirements made upon military systems. Risk associated with system development might represent one such additional judgment criteria. Figure 4 depicts the manner in which individual criteria contribute to overall system worth

through individual weighting functions (12:10).

An evaluation of space-based radar systems is well suited to the systems engineering approach of problem solving. Incorporated in the systems engineering methods are consideration of the complexity of a large-scale system and the dependence of subsystems in the overall performance. Systems engineering allows for judgment of overall system and subsystem characteristics based on criteria that relate directly to design and performance.

The Analytic Hierarchy Process

The analytic hierarchy process ties in well with the concepts of systems engineering. Systems engineering requires a method to facilitate making trade-offs in the optimization step. AHP is a suitable choice for this step. AHP is an effective analytical tool by which alternative solutions can be evaluated.

Suitability. AHP is particularly well suited to large-scale systems. Like systems engineering, AHP addresses the problems of a complex decision environment. This method incorporates an individual's experience in restructuring the problem in a more manageable form:

> The analytic hierarchy process enables decision makers to represent the simultaneous interaction of many factors in complex, unstructured situations. It helps them to identify and set priorities on the basis of their objectives and their knowledge and experience of each problem [30:12].

AHP has the capacity to deal with the multiple issues of a

complex system without restricting the flexibility of systems engineering. Within the global approach of systems engineering, AHP retains the ability to focus the many impinging concerns into prioritized objectives. This process is essential to arriving at a solution:

> To deal with unstructured social, economic, and political issues, we need to order our priorities, to agree that one objective outweighs another in the short term, and to make trade-offs to serve the greatest common interest. But it is often difficult to agree on which objective outweighs another--particularly in complex issues where a wide margin of error is possible in making trade-offs [30:4].

Advantages. AHP incorporates reasoning in the way some other analytical tools fail to provide. Saaty identifies two ways to view a system, the deductive approach and the systems approach (30:5). He further suggests that, because AHP incorporates value assessment by weighting subsystems, the analytic hierarchy process combines the best of both worlds (30:5-6). AHP derives much of its utility by processing the weighted value assessments through matrix mathematics. The mathematical approach lends computational speed and provides a logical foundation to the often ambiguous nature of subjective logic. In a sense, hidden relationships can be derived through secondary association of variables. A structure is then present through these linkages.

Hierarchical Structure. For large systems like space-based radar, a path must relate the issues at the lower levels to the overall objective. The analytic

hierarchy process provides "a useful theory for analyzing the impacts of the elements in the lowest levels on the overall objective, or focus, of the hierarchy" (32:141). By tracing through the hierarchy and making the comparisons at the subsystem level, one can arrive at the preferred alternative. Applied to space-based radar, this would allow the analyst to relate technology issues through subsidiary objectives to the overall mission objective and, thus, arrive at the best choice for a space-based radar.

Objectives

To thoroughly analyze the function of a space-based radar, clear statements of purpose are necessary. These statements of purpose take the form of objectives. In the military, these are the mission objectives. Planners arrive at these mission objectives in response to a perceived threat and under the guidance specified by military doctrine.

The objectives allow us to approach the problem from the systems analysis standpoint. De Neufville and Stafford point out, "all analyses are based upon some set of objectives, and it seems better, by far, to define them openly" (16:7). They further clarify this by stating, "Much of the value of systematic analysis lies in the identification of objectives and the clarification of issues" (16:7). This brings to mind the question of how to get to the root of

the problem of complex systems which span a broad range of issues for which the systems analyst has little background. The proposed solution lies in the analyst's ability to "challenge loosely stated goals defined by clients or professionals from other fields and thus to identify the fundamental purpose of a system"(16:7). Thus, by dealing with those individuals most informed on the detailed interrelationships and asking directed questions, one can gain understanding of the problem.

The analysis process is an iterative approach that allows for revision of the original design. Having completed the analysis, the increased understanding can be recycled into better defining the original objectives to obtain a more precise definition of the stated problem. The Military Space Systems Technology Plan provides the first iteration for analyzing many space systems including space-based radar. As such, the MSSTP provides the departure point that leads to a more precise understanding of space-based radar objectives. In essence, the space-based radar concepts identified in the MSSTP have expanded to the extent that a choice must be made between concept options. The second iteration then involves the ability to make trade-offs based on stated objectives.

The methodology presented in Chapter 4 outlines an approach which performs this second iteration. Objectives that are stated in the form of mission requirements play an integral role in making the various system trade-offs. The

degree to which the system is able to accomplish objectives is often specified according to some figure of merit. To be valid, these figures of merit must be based on a technical knowledge of the system. The next chapter supports the formulation presented in Chapter 4 and demonstrated in Chapter 5 by reviewing some of these technical considerations that are important to space-based radar.

III. Technical Considerations for Space-Based Radar Trade-offs

Introduction

Selecting an appropriate space-based radar to provide air surveillance presents a challenging problem. Not only do managers and engineers have to deal with traditional radar problems, but they must also deal with integration problems particular to the space environment. A review of traditional radar relationships in light of the additional constraints imposed by the space environment will help give an appreciation for these complexities.

The intent of this discussion is not to explain radar theory in depth, but to highlight material particularly applicable to space configuration options. Exploring the parameters which affect space-based radar performance will expose trade-offs that complicate the decision process. A review of associated terminology should also be helpful in the following chapters. By reviewing radar fundamentals, the reader can more effectively apply the methodology described in this work to the technical relationships that influence the decision process.

Although, one could devote a great deal of time to radar issues, the intent of this chapter is to highlight only those considerations that will influence design trade-offs in the subsequent discussion. Should further review

be necessary, the text, Introduction to Radar Systems, by Skolnik provides an excellent source of reference (38).

The role of space-based radar concerned with in this analysis is restricted to surveillance of targets in the background of earth features. Clearly, there are other potential applications of space-based radar. Radar to assist in space object identification, collision avoidance, and space rendezvous have been identified as possible roles for space-to-space systems that discriminate targets from the space background (8:120; 10:54-55; 39:34-4; 46:56). Such space-to-space systems are not under consideration here, but could, with minor changes, be incorporated into a similar example. Since the purpose here is to demonstrate the methodology, their addition to the problem would not significantly increase reader understanding.

Space-Based Radar Missions

The concept of fielding space-based radar systems offers potential advantages to defense posture. Advanced warning of airborne attack is one potential benefit afforded by space-based radar. Brookner and Mahoney postulate the following needs:

> the ever-increasing threat of long-range air launched cruise missiles (ALCMs) has aroused new interest by both the Air Force and the Navy in the application of satellite radar for air surveillance. The Navy is faced with the need to extend the defense perimeter surrounding their task forces well beyond ranges that can readily be supported by airborne sensors. The concern

> of the Air Force is air defense of CONUS, particularly the northern approaches [9:465].

Cline and Torretta further echo these mission concerns:

> A key factor in the utility of such a surveillance system is the capability to correctly associate intermittent reports of moving ships and aircraft, in order to successfully initiate and maintain target tracks in the presence of background traffic [13:123].

Worldwide coverage and all weather capability are features that enhance space-based radar's value in accomplishing these surveillance missions. These experts agree on the advantages afforded by space-based radar and recognize the benefits in pursuing this technology.

To obtain the full benefit of space-based radar technology, issues of performance and design must be firmly established. These two qualities, while distinct, are unquestionably dependent upon one another. Performance and design are essential characteristics which drive technology trade-offs. Together, they provide a measurable input upon which the decision maker can evaluate alternative systems.

Performance specifies the functions needed to meet requirements while design dictates how those functions are achieved. Performance requirements that evolve from mission objectives may not always be attainable. Attainable performance actually stems from the associated physics issues and is specified by appropriate mathematical relationships that govern the task. Design specifies how performance is achieved. While design often imposes limits on

attainable performance, it also offers flexibility in the form of alternative ways to meet performance goals. The distinct yet interactive nature of performance and design provides a convenient means upon which to distinguish the technical issues associated with space-based radar trade-offs.

Space-Based Radar Performance

Radar provides the capability to accomplish several types of remote sensing tasks. Detection and ranging are perhaps the most well recognized of these tasks. These tasks translate into the surveillance and tracking activities required of space-based radar for air surveillance missions. Because radar exploits the properties of electromagnetic radiation, radar systems can discriminate target range and azimuth with precision. Physical laws that govern electromagnetic wave propagation define the capabilities and limitations associated with radar applications such as these (37; 47:96).

The relevant parameters for radar performance arise from the radar range equation. In practice, this equation may take many forms. Often direct relationships between all parameters are not readily apparent. The basic form of the radar range equation may be altered slightly in order to reflect surveillance considerations. Skolnik does just this and specifies the surveillance form of the radar range

equation as (38:64):

$$(R_{max})^4 = \frac{P_{av}\ A_e\ \sigma\ E_i(n)\ t_s}{4\ \pi\ k\ T_o\ F_n (S/N)_1\ L_s\ \Omega} \qquad (1)$$

where

R_{max}	=	maximum radar range
P_{av}	=	average transmitter power over the pulse-repetition period
A_e	=	antenna effective aperture
σ	=	radar cross section of target
$E_i(n)$	=	integration efficiency
t_s	=	scan time
k	=	Boltzmann's constant
T_o	=	standard temperature
F_n	=	noise figure
$(S/N)_1$	=	signal-to-noise ratio required at receiver output
L_s	=	system losses not included in other parameters
Ω	=	the angular region to be searched in the scan time

Fundamental relationships expressed in the radar range equation restrict radar surveillance and track functions regardless of basing mode. The underlying problem is illuminating the target from an extended range with enough power to sense reflected pulses. A radar must then possess effective signal processing to interpret the signal for maximum information. Because of the great distances involved, the problem of remote sensing with radar from space is especially difficult. This situation is complicated by the fact that targets in air surveillance scenarios are relatively small and masked by natural background clutter or by electronic means.

<u>Power and Aperture</u>. The power-aperture product exhibits a strong influence on range performance as evidenced

through the radar range equation. All other parameters being equal, radars with larger effective apertures and higher radiated power operate at longer ranges. The power-aperture product provides a measure of this combined effect. The mix of power and aperture can be traded off to arrive at a specified power-aperture product for a desired performance. Design constraints determine the degree to which such trade-offs are possible.

Scan Time. Scan time is another important consideration evident from the radar range equation. This parameter is a function of the time spent on the target, the area of the directed beam, and the total area to be viewed. The satellite motion or scanning system type and motion will have a bearing on the values that these parameters can achieve. A particular design will reflect these scan considerations.

Frequency. Although not readily apparent from the radar range equation, frequency significantly influences radar system performance. Lower frequencies are generally more favorable for attaining large power and large apertures (38:64). Radar footprint also becomes larger with lower frequencies (9:469). In addition, attenuation, due to weather and the atmosphere, decreases with frequency as does clutter return (9:469).

Higher frequencies, however, do offer some advantages over lower frequencies. Resistance to jamming is one such advantage due to both the broad operational bandwidth that

can be employed and the ability to operate with a narrow main lobe beamwidth (9:469). For the same level of antenna gain, higher frequencies allow smaller antenna aperture dimensions than lower frequencies (39:11-23). Fading due to ionization and effects of auroral clutter are also less persistent at higher frequencies (9:469).

The combined effects on the radar signal at high and low frequencies effectively bound the range of acceptable frequencies for air surveillance by space-based radar. Barring dramatic breakthroughs in radar technology, candidate frequencies lie in the L- and S-bands. The center of these bands correspond to approximately 1.3 gigahertz (GHz) and 3.0 GHz respectively (26c:2-39). Below L-band, atmospheric fading is severe and resolution suffers, while clutter return and attenuation due to precipitation become high above S-band (26c:2-36; 9:469).

Radar Cross Section. Radar cross section is an indicator of the target's radar reflective property. More precisely, Skolnik defines the radar cross section as:

> the (fictional) area intercepting that amount of power which, when scattered equally in all directions, produces an echo at the radar equal to that from the target [38:33].

Radar cross section, for the most part, is not simply a direct relationship to target area (38:33). Radar cross section is aspect sensitive and, thus, dependent on viewing angle. Most radar cross sections are determined either experimentally or by computer (38:38).

In a subtle way, radar cross section also brings to light the dynamics of the target environment. The radar must dwell on the target for a given period of time. Thus, a target's velocity and capability to maneuver influence the amount of time that the target radar cross section is subject to scan within the radar's field of view (24:127-128). With this dependency in mind, it is important to transition from the parameters of the radar range equation to intermediate performance parameters within the context of the air surveillance scenario.

In order to relate the air surveillance mission to both radar parameters and target characteristics in more understandable terms, we must capture the performance in terms of some set of intermediate parameters. The radar parameters alone do not fully express how performance relates to design choices. These parameters then link the parameters from the radar range equation to operational performance requirements. They act as appropriate figures of merit upon which to judge performance.

Review of available literature shows that four issues and their associated figures of merit dominate space-based radar performance concerns. These issues are search rates, clutter rejection techniques, report-to-report correlation, and threat survivability. Considering these four categories provides a way to relate operational demands to the underlying physics. Establishing this relationship is important because the underlying physics provides the

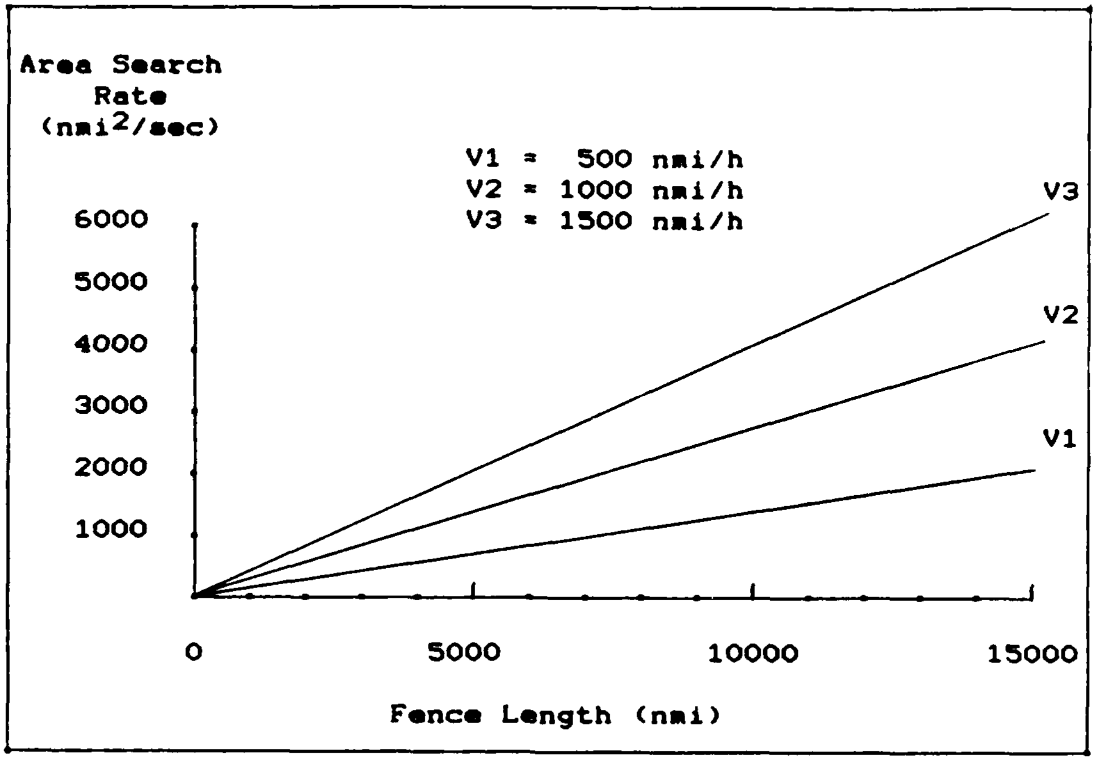


Figure 5. Area Search Rate Trade-offs (9:466)

guidelines for making design trade-offs.

Search Rates. Search rates pertain to both the detection and tracking functions of the radar. To initially identify the target, area search rate evolves from the maximum velocity of the target perpendicular to a radar fence of a specified length (9:466). Once identified, the number of targets, area of the radar footprint, and track update interval specify an equivalent track area search rate to maintain track on a number of previously identified targets (9:466). Figures 5 and 6, results from Brookner and Mahoney's paper, provide a graphical representation of the multiple factors that contribute to making these search

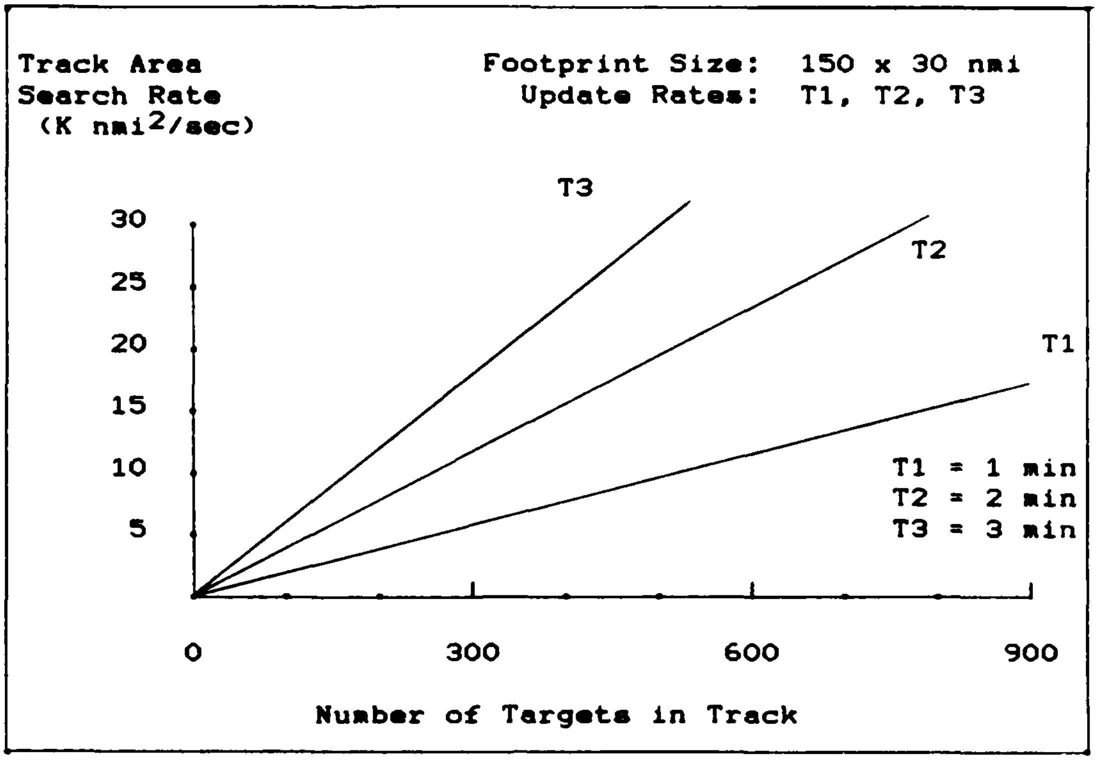


Figure 6. Track Area Search Rate Trade-offs (9:467)

rates effective intermediate parameters for judging space-based radar trade-offs.

<u>Clutter Rejection</u>. The ability to distinguish targets from background features also plays an important role in space-based radar performance. Clutter arises from any unwanted radar echoes such as reflections from land, sea, or atmospheric elements (38:470). This backscattering can obscure a potential target:

> A satellite radar looking down on earth to detect airborne targets must reject clutter return that can be five or six orders of magnitude larger than the target return [9:467].

Moving target indication (MTI) and pulse doppler are two

means for accomplishing clutter rejection. Both use the principle of doppler frequency shift to discriminate moving targets from the stationary clutter (38:101), Unlike synthetic aperture radar (SAR) processing, MTI and pulse doppler provide clutter cancellation in the shorter dwell times that are conducive to high area search rates and multiple target tracking (9:469). Brookner and Mahoney emphasize the virtues of MTI or pulse doppler compatibility with other clutter cancellation enhancing techniques while pointing out SAR's requirement for high peak power to attain the necessary resolution (9:469).

Report-to-Report Correlation. Identifying and maintaining track on a specific target among other background targets presents a problem equally complex to that of clutter rejection. Motion feasibility algorithms support this requirement to correlate space-based radar observations. Cline and Torretta claim:

> Given two SBR reports of detected targets, taken at different times but in the same general location, some logical scheme is needed to determine whether or not the two reports represent observations of the same target, i.e., are associated with each other [13:123].

The correlation algorithm for report-to-report correlation takes into account factors such as revisit time, missed detections, target maneuvering, background targets, radar errors, and false alarms (13:123). Because the algorithm is probabilistic in it's approach, the outcome expresses the radar's ability to uniquely associate targets with tracks

as a probability of correct association (13:123-127). The correct association decision rate then provides a means to judge radar performance in the area of report-to-report correlation.

Survivability. Survivability issues permeate all aspects of space-based radar performance. This area is particularly broad due to numerous ways to kill or disrupt radar system performance. It will suffice to say that any deposition of energy in excess of 10 K joules if deposited on a small area within a few seconds will effectively degrade space-based radar performance (3). This damage will occur regardless of potential delivery mode to include kinetic projectile, laser beam, or particle beam weapons. A total integrated radiation dose of 10^6 rads silicon, a transient radiation dose of 10^5 rads silicon per second, or neutron fluence on the order of 10^{10} neutrons per square centimeter will also have lethal consequences (3; 27). Consideration must be given as to ways to prevent coupling of lethal energy into a targeted space-based radar as well as methods for shielding from radiation effects.

The electronic warfare threat is also an important survivability issue. This threat, most frequently in the form of jamming, can be partially countered by means of controlled sidelobes and adaptive nulling. Since high sidelobes make jamming easier, directing most of the radar energy into the main beam to attain low sidelobes is desirable (38:227). Attaining these low sidelobes normally

requires an antenna of high gain with aperture illumination tapered down near the edges (38:227). Adaptive nulling also minimizes jamming interference by adjusting amplitude and phase across the aperture to compensate for adverse effects (38:332). Placing a null in the desired direction effectively cancels unwanted sidelobe interference (38:333). Both of these electronic counter-countermeasure (ECCM) techniques, attaining low sidelobes and adaptive nulling, place great demands on antenna type and design tolerances. Clearly, performance requirements from survivability issues impose severe restrictions on design and invoke an whole new environment of trade-offs.

Having discussed performance both from the perspective of the radar range equation and with selected intermediate issues in mind, it is appropriate to delve into trade-offs borne out of design considerations. The following discussion will serve to show how the decision maker is drawn into the decision process by the conflict between design constraints and performance requirements. Judgment and value assessments begin to creep into the preliminary design stages as an attempt by the decision maker to attain the optimal system. This complication will become more clear with a look at design concerns.

Space-Based Radar Design

Several US corporations and radar technologists have

invested considerable effort in identifying possible space-based radar configurations. Given the above performance concerns, a review of some limiting design factors that have come to light from the civil effort serves to highlight possible concept options. This review helps to expand the decision base for choosing between concept options. The discussion also justifies the need for the structured support hierarchy developed in the space-based radar methodology of subsequent chapters. Design topics pertinent to space-based radar presented here include constellation geometry, payload concerns, antenna configuration, scan implementation, and feed methods.

Geometry. The location of the space-based radar platform is a design consideration which dramatically affects radar system performance. Together, the scan technique, orbital altitude, and inclination specify the radar geometry. This geometry determines the field of view and type of coverage that the radar can provide. Figure 7 depicts this geometry for a single satellite. Notice, the grazing angle and nadir hole formed around the normal look angle. Both limit radar performance. At grazing angles less than 3 degrees, atmospheric fading and ducting restrict accurate radar detection (9:469). At the other extreme, a 50 degree search limit and a 70 degree track limit define the extent of the nadir hole (9:469; 18:13). Brookner and Mahoney reveal:

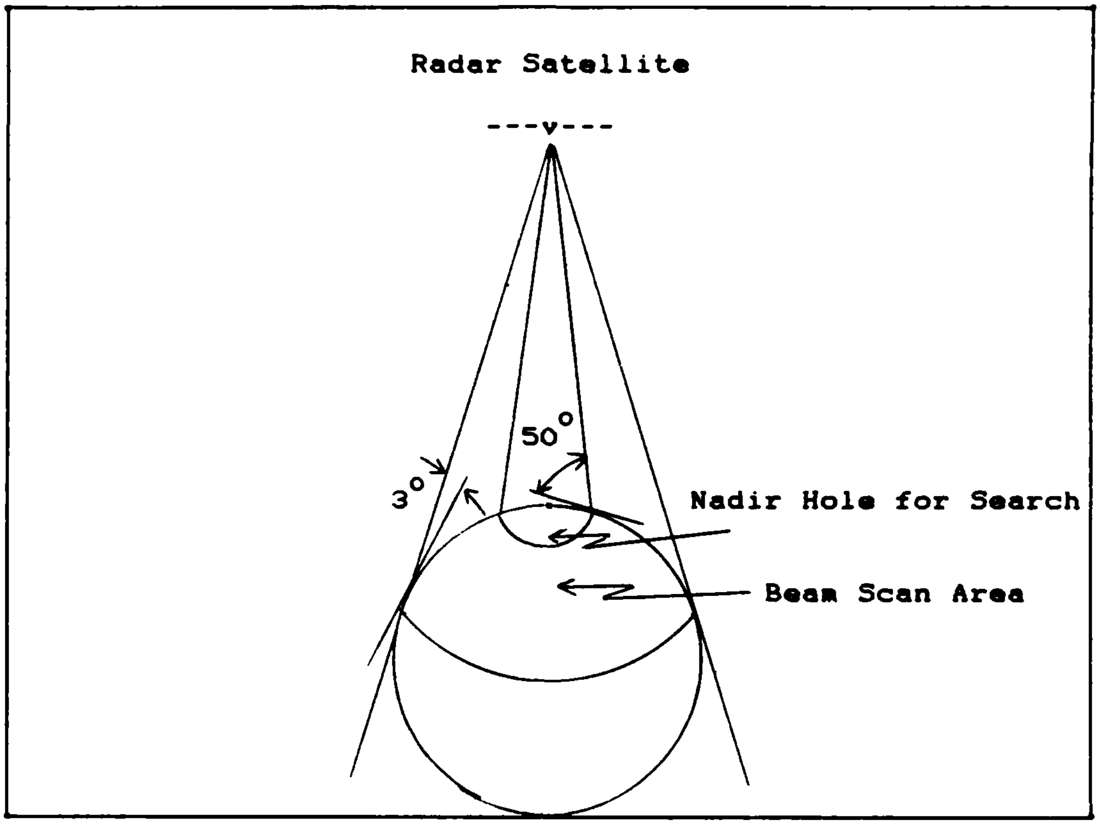


Figure 7. Single Satellite Geometry (18:14; 9:470)

> single satellite coverage area increases with altitude to about 3500 miles and then decreases as the nadir hole increases more rapidly than the usable coverage band [9:469].

Limits to a single satellite's coverage are a function of operating mode and are imposed by grazing angle and nadir hole constraints. Reliable search exists in the 3 to 50 degrees grazing angle range while track can function effectively from 3 to 70 degrees.

Due to the variation in area of coverage per satellite with altitude, the number of satellites required for total coverage is a function of the geometry. The decision

maker's preferred degree of coverage greatly affects the number of satellites required in a particular constellation. Choices may range from continuous to non-continuous coverage on either a local area or global scale. A description of the operational environment must include a statement of the user's tolerance for acceptable gaps in coverage. Acceptance of some intermediate gaps in coverage allows fewer satellites to be used at a given altitude (9:471). If gaps in coverage are not permissible, the number of satellites required is more sensitive to changes in altitude with the number increasing at lower orbits (9:471). Likewise, required scan capability for full horizon-to-horizon surveillance increases as altitude decreases (9:471). Many other considerations such as range ambiguity, natural radiation effects, propulsion to orbit, and threat vulnerability also must be taken as legitimate concerns in making trade-offs to arrive at a suitable geometry.

Payload Factors. Similar in scope to survivability issues, size and weight constraints influence virtually every aspect of design. More explicitly stated:

> These two could very well be the driving parameters in overall system design. Any attempt made at alleviating constraints caused by the other factors almost always results in a change in weight and size parameters [26d:4-11].

Launch weight and payload capacity severely decrease design flexibility. This concern is particularly important when designing systems that must provide a high enough

power-aperture product to meet performance requirements. In effect:

> the power-aperture product required for a satellite radar above about 2500 nautical miles results in a radar payload weight, using near-term technology, that exceeds with weight capability of a single shuttle launch [9:470].

As a result of these restrictions, a choice between designing for single launch or for on-orbit assembly arises as another trade-off to consider.

Antenna Configuration. Antenna choice is a major consideration in the design of space-based radar. The type of antenna and scan method are interrelated. Because of this relationship and the impact that antenna choice has on radar system performance, it is appropriate to discuss the antenna subsystem in more detail.

Planar arrays are especially good candidates for space-based radar antennas. Coupled with a digital computer for signal processing, planar array antennas have led to the implementation of track-while-scan systems. These systems are particularly useful for missions of air surveillance and, hence, are prime contenders for space-based applications.

Track-while-scan systems take advantage of the planar array's ability to operate in a multi-mode configuration. The radar can actually function in more than one operational mode. For instance, the radar can track several individual targets while still searching the entire objective area to provide warning on new targets (20:9-15;

38:279). Skolnik emphasizes the advantage with such a system when he states:

> The two-dimensional planar array is probably the array of most interest in radar applications since it is fundamentally the most versatile of all radar antennas [38:279].

Scan Implementation. Track-while-scan radars operate with either mechanical or electronic scanning systems. While mechanical systems are relatively simple, the advantages afforded by electronic scanning systems provide strong incentive to employ such systems in space-based radar.

Radars accomplish electronic scanning as a result of the electronic beam steering capability afforded by planar array antenna design. Electronic feed switching, frequency steering, and phase steering are the three types of electronic scanning used in radar (20:9-17). Of these, phase steering dominates as the technique most supported for surveillance radar applications from space.

Feed Methods. For space-based interests, there are two primary methods by which the radar signal is fed to the array. Array feed is by either a parallel-fed method or space-fed method. The parallel-fed is often termed corporate-fed due to its similarity with the parallel tree structure common to corporate organizations (38:285). By feed mechanism, designers mean the network by which radio frequency (RF) power is divided and distributed to individual elements of the antenna array (38:306).

The corporate feed distributes the RF power in a parallel fashion to each element. In doing so, each array element has its own phase shifter and standard microwave channel to distribute power. A transmitter and receiver are located at each element. This arrangement enhances the radar's capability to radiate high power (38:309).

Unlike the corporate feed, the feed for the space-fed designs is physically separate from the antenna array plane. Hence, the RF power eminates as if from a point source incident on the antenna surface elements (38:306). This space-fed antenna comes in two basic configurations. Each is characterized by the direction of element illumination, one being refractive and the other being reflective. The refractive configuration functions like a space-fed lens by focusing or steering the beam at the array after having been illuminated from the rear by the RF feed. It does this by collecting the radiation with antenna array elements on the rear face, passing the energy through phase shifters, and re-radiating from elements on the front face of the antenna (20:9-22).

In contrast to the space-fed lens arrangement, the feed for the reflective type of design projects RF power toward the antenna, not to pass through the array, but to be reflected in the target direction. The plane of reflection is behind the individual elements so phase shifting occurs in both directions. Unfortunately, increased sidelobes and some beam degradation occur in the space-fed

reflector array. Aperture blockage resulting from the location of the feed between the array and target area causes these problems by disrupting the radiation pattern (20:9-22).

Although a wide variety of antenna and scan mechanisms have been proposed for space-based radar systems, the phased array arrangement appears most promising. Brookner and Mahoney review several antenna arrangements and support this assessment by concluding:

> The ultimate choice of scan implementation is clearly, then, full two-dimensional electronic scan and the trade-off lies between a space-fed lens array and a corporate-fed planar array [9:473].

Many trade-offs still exist. Envisioned corporate-fed designs are larger while space-fed designs appear to require more complicated deployment mechanisms (9:473). Both require very stringent surface tolerances that become even more critical at the higher frequencies (26d:4-11). The space-fed design, however, has the added complication of possible unwanted vibrational modes due to the structure extending the feed device out from the phased array aperture (26c:2-39). The space-fed designs would likely require all monolithic transmit/receive (T/R) modules while either monolithic or hybrid modules would be plausible for corporate-fed designs (9:473).

Modules. The extent of T/R module development is a driving force behind space-based radar technology. The push is for small and light monolithic T/R modules that

exhibit acceptable performance. The number of modules required varies dramatically with frequency. Consequently, lower frequencies require substantially fewer modules and, therefore, are more desirable from the cost, weight, and size perspective. For example, the number of S-band modules required could be close to 1 million, at least an order of magnitude greater than the number of L-band modules required (2). From a performance perspective, however, S-band modules offer "significant advantages in terms of clutter spectrum spread, Faraday rotation loss, target resolution, target identification, and ECCM" (26c:2-39). Several descriptors of T/R module design and performance are required to effectively characterize these devices:

> The T/R module figure of merit involves a combination of cost, weight, size, efficiency, reliability, phase and amplitude stability, and achievable output power and noise figure [26d:4-7].

Power distribution and device technology, as integral parts of module development, greatly influence these figures of merit. Continuous wave ratings of solid state devices indicate that bipolar transistors provide better power performance below 4 GHz while impact ionization transit time (IMPATT) diodes and field effect transistors, respectively, dominate between 4 GHz and 10 GHz (26d:4-9). Low noise receivers also vary with frequency. Clearly, there a numerous trade-offs to make between T/R module performance and overall radar system function as well as between individual devices within the T/R module subsystem

itself. Not the least of these would include manufacturing concerns to support large aperture, phased array construction.

Summary

The performance and design considerations presented in this chapter illustrate only some of the many interdependencies that support radar trade-offs. The list of issues is far more extensive than the brief analysis presented here. This review of radar trade-offs, however, helps to establish some bounds within which trade-offs are physically possible. Furthermore, the review shows the evolution from basic radar parameters to intermediate figures of merit and, finally, to operational concerns.

Due to the many considerations discussed in this section, designers must take great care in detailing proposed systems. Since design choices are the engineer's manifestation of trade-off decisions, this effort to justify choices will allow decision makers to fully comprehend the implications of a specific design. This action may also bring out the logic behind choosing one approach over another, whether because of technological barriers, unfamiliarity with operational demands, or bias.

Clearly, the decision maker must have access to the numerous technology issues on space-based radar to make an informed choice. Hopefully, a review of performance and

design concerns has provided an appreciation of this extensive technical background. The temptation, however, is to attempt to assimilate all the facts internally and arrive at an intuitive decision as to the correct choice. A methodology to lead the decision maker through a decision structure proposes to provide a much more rational approach.

This rational approach demands that military decision makers both specify operational demands and recognize technology limitations. At the same time, the decision maker must recognize that the decision process is not solely a technological optimization. Values, experience, and social forces also contribute to reaching a satisfactory solution. The methodology presented in the next chapter combines all of these features from the decision environment to outline an approach for assessing technology trade-offs.

IV. Derivation of a Methodology for Assessing Trade-offs

Introduction

A well-developed methodology supports decision makers in their attempt to understand complex engineering problems. Selecting an appropriate methodology, therefore, is instrumental in bringing to light the competing issues that affect choosing an appropriate space-based radar design. Experts in decision theory recognize the analytic hierarchy process as being particularly effective in assessing preferences related to decisions in complex systems (30:2; 31: 156-157; 49; 50). This analytical tool has the additional benefit of being adaptable to the framework of the Military Space Systems Technology Plan (28:6-11). Because space-based radar issues are best delineated within the MSSTP structure, such compatibility between the MSSTP and AHP contributes to a better understanding of the space-based radar problem. Having recognized these relationships, this chapter highlights how the decision maker can implement AHP to structure SBR issues and subsequently make trade-offs between concept options.

Application of AHP

Merits. The analytic hierarchy process offers several advantages in evaluating space-based radar options.

AHP is simple, flexible, and sensitive to realistic value judgments. These qualities support effective decision making.

AHP simplifies the decision making process through a functional hierarchy. The mind logically decomposes issues of complex systems by compartmentalizing ideas into subsets (29:57; 15:239-256). This division allows the mind to simplify relationships. AHP's functional hierarchy captures this thought process and easily displays it in hierarchical form for the decision maker. The problem is no longer unstructured and interrelationships are more apparent.

AHP is also flexible enough to be molded to the changing decision environment. With the rapid pace of technological change, a methodology for making choices must remain flexible. New developments in engineering disciplines may alter the relative appeal of concept options. In addition, outside pressures on the decision maker may change the value system upon which a decision is based. AHP permits expansion within the hierarchy to incorporate these changes. Levels can be added or removed and selected element weights can be altered to accommodate change.

In addition to flexibility and simplicity, AHP adds realism to the space-based radar model. Subjective opinion and intuition can be incorporated into the decision process. These qualities of decision making are often missing in other techniques. Saaty claims:

> To be realistic our models must include and measure all important tangible and intangible quantitatively measurable, and qualitative factors [29:1].

AHP exhibits the unique ability to deal with both objective reality and intuition as reflected in a decision maker's judgments. Especially in the case of future space systems, decisions must be based partially on the decision maker's ability to predict outcomes. Such judgment comes from experience and is admissible in AHP. This added realism, along with the simplicity and flexibility described previously, contribute to an effective analytical methodology for space-based radar. These merits support the effort to apply an AHP methodology to space-based radar.

Implementation. The analysis of pertinent space-based radar issues through the AHP methodology involves three phases. The first phase consists of developing a functional structure by establishing a hierarchical system of relationships. Phase two involves a pairwise comparison of elements within the functional hierarchy to arrive at weightings. Finally, the third phase combines individual weightings to arrive at an aggregate value upon which to judge alternative concepts. Saaty refers to these steps as hierarchical decomposition, comparative judgment, and synthesis (32:141).

Hierarchical Decomposition for SBR

The principle of hierarchical decomposition orders

space-based radar issues into an organized structure for the decision maker. This process consists of breaking down space-based radar issues that influence the decision process into homogeneous groups. Such an activity exposes fundamental dependencies that ultimately influence how a decision maker judges the value of a particular space-based radar design. Elements of the same degree of importance in the decision process comprise a single level within the hierarchy. The detail to which each level is subdivided into more specific sublevels is problem dependent.

In the context of the space-based radar problem, this hierarchical development is of a dual nature. The criteria upon which the senior decision makers base their value assessments are seemingly far removed from individual technology issues. These measures of overall worth reside on a high level of the hierarchy and reflect desired system optimality. Each specific technology issue, however, is individually characterized at a much lower level of the hierarchy. The MSSTP provides the needed factual support to relate each issue's potential contribution to a particular concept option under review.

This dual nature of the hierarchy can best be incorporated by specifying a decision hierarchy and a support hierarchy. The elements of each are by necessity interdependent and linked together through the concept options common to both. Exploring this structure serves to lay the foundation upon which space-based radar concept options

can be compared. It also allows us to draw a distinction between value assessments and the supporting data from which concepts derive their identity.

The Decision Hierarchy

The Focus. The overall objective of the space-based radar concept forms the highest level of the decision hierarchy. This objective should capture the purpose for which the system is employed. The previous chapter provides the background to establish this objective. The stated objective for the space-based radar considered here is to provide air surveillance (warning and tracking) of air-breathing targets. This overall objective is the focus which all subsequent levels of the hierarchy support.

Intermediate Criteria. The second level of the hierarchy consists of the primary decision level which is closest to the overall system objective. In essence, this is the level at which the more senior decision makers become most involved. As such, the elements within this level must represent the criteria of highest concern to these senior managers. At this level, decisions are based strongly on the relative values assigned to each element. The values assigned to these elements reflect the cognitive skills of higher level managers to synthesize multiple concerns. There is no single correct set of weightings in the sense that no decision maker can fully predict how

important each criteria will be in the future. Assuming that all of the criteria are not of equal importance in achieving the overall goal, each must then take on a degree of importance relative to the others. The decision maker allocates these priorities.

In this methodology, four elements comprise the second level of the decision hierarchy. These elements are performance, cost, schedule, and risk. Each satisfies the fundamental principle required of hierarchical structuring. Saaty explains:

> hierarchical decomposition requires that the elements of the last or bottom level of the hierarchy be meaningfully pairwise comparable according to elements in the next higher level, these in turn according to elements in the next level, and so on up, to the focus of the hierarchy [32:141].

The four elements of the second level are all issues that influence the degree to which a decision maker is willing to commit resources to the overall objective. All elements, therefore, relate upward in the hierarchy. These elements also provide the linkage downward to the third and only remaining level of the decision hierarchy, that of the concept options. Thus, these four elements serve as effective criteria for meeting the overall objective and link together two levels of the decision hierarchy.

The selection of performance, cost, schedule, and risk is also appropriate from the systems engineering standpoint. These four factors are included in de Neufville and Stafford's list for systems engineering referred to in the

previous chapter. Even though maintainability is not explicitly listed, it is implicitly included in the lowest level of the hierarchy as a subset of performance. The Air Force Space Technology Center also recognizes these elements as being essential to space technology related decisions. AFSTC recommends:

> decision makers need to assess cost, risk, and schedule trade-offs, and in some cases applicability to non-space programs, before making final technology issue priority choices [26h:4-1].

Some decision makers may desire to add other elements to this level. However, since the intent here is not to model a particular decision maker, these particular mid-level elements provide an excellent point of departure in illustrating the methodology.

Alternative Concept Options. The radar options form the bottom level of the decision hierarchy. Each option can be described in terms of each element of the next highest level. For example, a specific option will have associated with it a certain performance, cost, schedule, and risk. Hence, the principle of hierarchical decomposition is satisfied. By ensuring that the number of these options is limited to less than seven, the problem remains more manageable (29:57; 15:245). Figure 8 portrays the relationships between levels and the respective elements within the decision hierarchy. The basic decision structure is now in place. The outcome, however, is only as good as the ability to characterize a particular concept option.

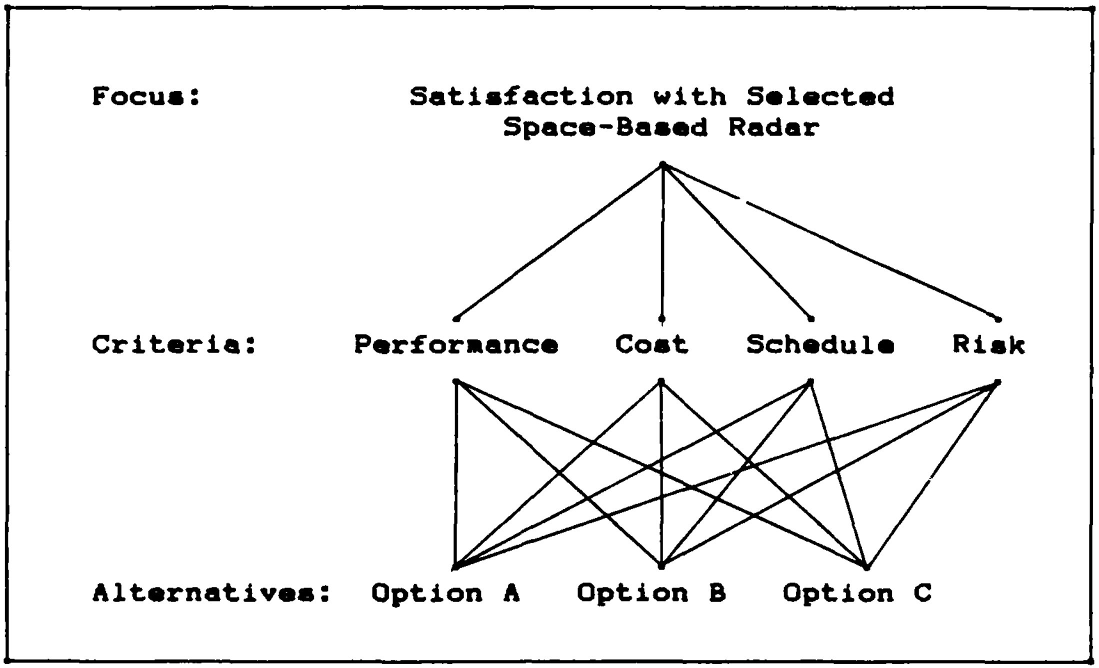


Figure 8. The Decision Hierarchy

The concept options occupy a unique position in the overall methodology. They are the common elements in both the decision and support hierarchies. The radar options function as the bottom element of the decision hierarchy and the top element of the support hierarchy. As part of the decision hierarchy, they relate to the decision maker in terms of overall value assessment. As part of the support hierarchy, they establish the relationship of technology issues through technology disciplines to a particular radar option under consideration. Each radar option must be fully characterized before it can effectively function as a bottom element in the decision hierarchy. The support hierarchy provides the radar option with its identity.

The Support Hierarchy

The support hierarchy aids the decision maker in understanding the distinguishing features of each particular radar alternative. This structure furnishes the decision maker with the facts upon which trade-offs can be based. The available information stems from the fact that concept options primarily derive their identity from two sources. Options are characterized both by performance parameters and by the technology required to meet that specified performance. Specifics of performance and design must be clear in order for decision makers to make choices between alternative systems. The support hierarchy establishes the concept option, performance, design, and technology linkages and presents them in a convenient fashion for the decision maker.

Separating the support hierarchy from the decision hierarchy allows the methodology to benefit from the substantial research already available. This dual nature easily incorporates the important contribution that the MSSTP provides in making trade-offs between space-based radar concept options. The MSSTP provides valuable input data for making critical assessments of the contributions that individual technology issues provide to a specific option. In designing an approach, it is important to recognize parallel efforts that will enhance the overall utility of this methodology. Acknowledging the MSSTP's potential

contribution to this methodology enhances its value. However, before explaining the MSSTP's influence, understanding the central structure of the hierarchy is necessary.

Concept Options. As stated previously, the concept option serves as the focal point for the support hierarchy. Each individual concept option occupies a position in the top level. In doing so, each concept option has its own independent support structure within the overall support hierarchy. The vertical tree, composed of the subordinate levels and their associated elements under a single option, uniquely defines that particular concept option at the top. Figure 9 displays this structure for the support hierarchy. Each element within this tree structure enhances the decision maker's understanding of the concept option in question. The total size of the support hierarchy will depend upon the number of concept options and the degree to which subordinate levels describe each option.

The support hierarchy should completely characterize all concept options for the decision maker. This characterization is the basis upon which the decision maker will evaluate the perspective systems. The evaluation itself takes place through the functional relationship of the decision hierarchy using AHP. Unlike the functional nature of the decision hierarchy, however, the support hierarchy is a structural hierarchy. That is to say, the subordinate levels serve only to build upon the understanding of the concept option in question. The importance of a single

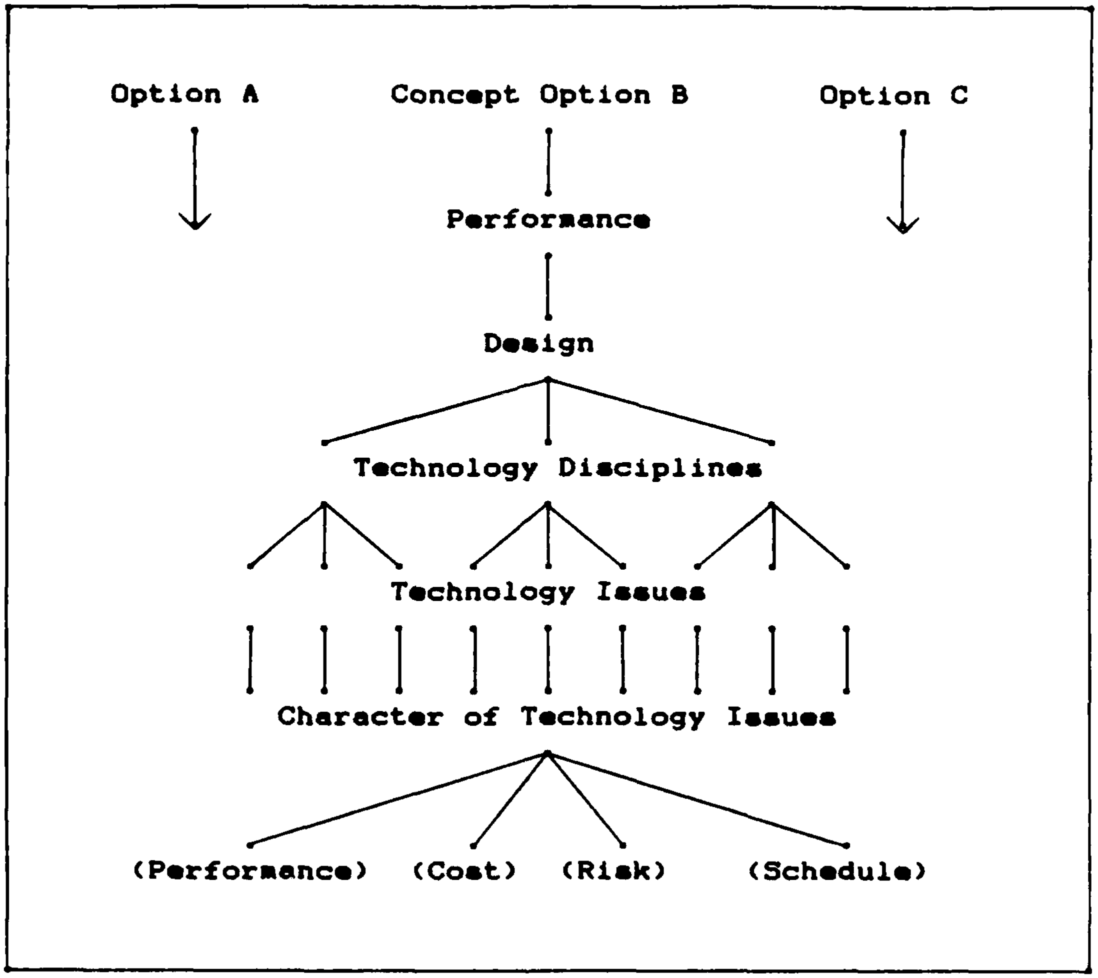


Figure 9. The Support Hierarchy

concept option is due more to the aggregation of all its subordinate features. Of these, performance ranks most important.

<u>Performance</u>. Overall performance of a particular option provides an immediate description of the capability of that option. For this reason, performance characteristics occupy the second level of the support hierarchy. The decision maker can readily compare performance to mission requirements. This comparison is particularly useful

because it directly relates to operational concerns. The stated performance clarifies what the system can accomplish and to what degree.

Performance characterizes the system according to a number of parameters. Selection of these parameters depends upon the particular system concept in question. All parameters, in some way, measure the ability of the concept option to accomplish the mission objective. For space-based radar, several of these were identified in Chapter 2. The value of intermediate parameters was recognized as a way to bridge the gap between fundamental radar parameters and operational measures. Area search rate is an example of one such intermediate parameter.

Because of the need to apply to several different types of space systems, the MSSTP specifies concepts according to six common performance requirements (26a:3-11). These are coverage, capacity, quality, timeliness, availability, and survivability (26a:3-11). This list of parameters is relevant to space-based radar and can also serve as a representative set in order to demonstrate how performance concerns function in this methodology.

Design. Design specifies how the desired performance is achieved. It is subordinate to performance and occupies a sublevel of its own. This level of the support hierarchy describes the engineering of component systems contributing to a desired performance. Design specifies the types of hardware and software required to make the

system perform. No lingering ambiguity should exist from undecided choices between alternative subsystems. If an alternative subsystem presents a viable course of action, that modification should be reflected in a completely separate concept option. Choices between competing designs should not be made at this level.

It is important to recognize that both performance and design, in concert, specify a concept option. For instance, two different systems might achieve the same level of performance, but their engineering design may be significantly different. Being of different design, the technology issues that relate to each design will be decidedly different. While performance of two radar systems may be the same, they are, in fact, different concept options in accordance with the methodology by virtue of their design differences. Thus, the decision maker must recognize the motivation behind labeling each option as being unique. The decision maker must know whether the distinction between concept options has been based on performance differences or on design differences.

MSSTP Technology Levels. The remaining levels of the support structure emphasize the input of contributing technologies. In descending order, technology disciplines, technology issues, and technology characteristics complete the support hierarchy. Much of the scientific data upon which decisions are based originates in these levels of the hierarchy. These levels are instrumental in evaluating

candidate systems. Their worth is due to the strong contribution of the MSSTP and the degree to which the AFSTC data base is able to characterize the specifics of each technology.

The MSSTP contributes to the methodology by identifying available technologies. The technologies which contribute to a system's design span several scientific disciplines. Often, the decision maker is unfamiliar with all technologies in such a vast number of areas. The decision maker, therefore, requires expert opinion in assessing the impact of alternative technologies. The MSSTP attempts to consolidate this expert opinion (42). It provides an organized, authoritative source for the state of potential technologies applicable to space systems. Technologies considered are also documented in the AFSTC data base listing of MSSTP technologies (44; 45). Any methodology for making space system trade-offs would clearly benefit from an approach that incorporates the features of the MSSTP.

Technology Disciplines. The MSSTP provides a logical division of space system technologies into technology disciplines. By supplying a common ground upon which to group technologies, the MSSTP lends supportive structure to the methodology presented here. The MSSTP divides the collection of technologies that relate to space systems into 17 disciplines. These disciplines appear in Table I. This division gives the systems analyst a starting point

Table I. MSSTP Technology Disciplines (26a:vii)

Information Processing	Power and Energy
Communications	Thermal Control
Radar	Man-In-Space
Electro-Optical	Survivability
Materials	Autonomy
Structures	Test and Evaluation
Manufacturing	Weapons
Propulsion	Environment
Guidance, Navigation and Control	

from which to break down a concept option's design. Since these disciplines are generic to all space systems, not all will necessarily apply to a single concept like space-based radar. However, these disciplines do provide general categories under which the decision maker can group technology issues applicable to concepts such as space-based radar.

The ability to group technologies into disciplines also provides a fundamental advantage in soliciting expert opinion. It allows a technologist to lend expertise to the methodology through the functional structure of the MSSTP. Through an effective interface with the MSSTP data base, a single technologist can contribute critical design inputs to any concept or concept option flagged as having that discipline in its makeup. This benefits not only the

space-based radar concept, but all other concepts to which a particular discipline pertains. Soliciting expert judgment in this way minimizes the time and effort required to substantiate viable technology alternatives.

Technology Issues. The MSSTP further divides technology disciplines into technology issues. Semantics are important in understanding technology issues. The term technology issue implies a timeframe. A technology activity only becomes an issue when the end product of that activity cannot be effectively implemented in a particular concept option by the required date. Hence, technology issues are also highly concept specific. As such, there may be technology issues that pertain to a particular concept option that are unique and, as yet, not defined in the present listing of MSSTP technology issues. This implies an expansion of the present MSSTP listing of technology issues.

The technology issues interface within the methodology in a multifaceted way. The technology issues relate to both a specific design and the associated performance. They act as the key elements which drive system integration. Technology issues are design dependent but drive performance. In addition, technology issues characterize the concept options. The attributes of cost, schedule, and risk are characteristics of each technology issue. While these attributes are embedded in the support hierarchy at the local level, the same elements apply to the decision

hierarchy, only in a global sense as criteria.

<u>Technology Issue Characteristics</u>. Characterizing technology issues provides an understanding of concept options. Taken as a group, the characteristics of all the technology issues that comprise a single concept option provide a decision maker with an overall interpretation of the performance, cost, schedule, and risk for that option. Enhancing the decision maker's ability to make assessments through this detailed description of technology issues is the whole purpose of the support hierarchy. The overall appraisal is possible only because the individual measures of performance, cost, schedule and risk for each technology issue are available in the form of expert opinion captured in the MSSTP data base. By reviewing the characteristics of all technology issues under a single concept option, the decision maker can establish preferences to accomplish trade-offs between options. These trade-offs are formally accomplished in the decision hierarchy through AHP.

Figure 10 summarizes the functional interaction of the decision and support hierarchies in support of the decision maker. Notice that each concept option possesses an overall performance, cost, schedule, and risk value. This appraisal of a single option's overall performance, cost, schedule, and risk is a direct result of the support hierarchy's ability to allow a collective assessment of all the individual performance, cost, schedule, and risk measures associated with the constituent technology issues. Thus,

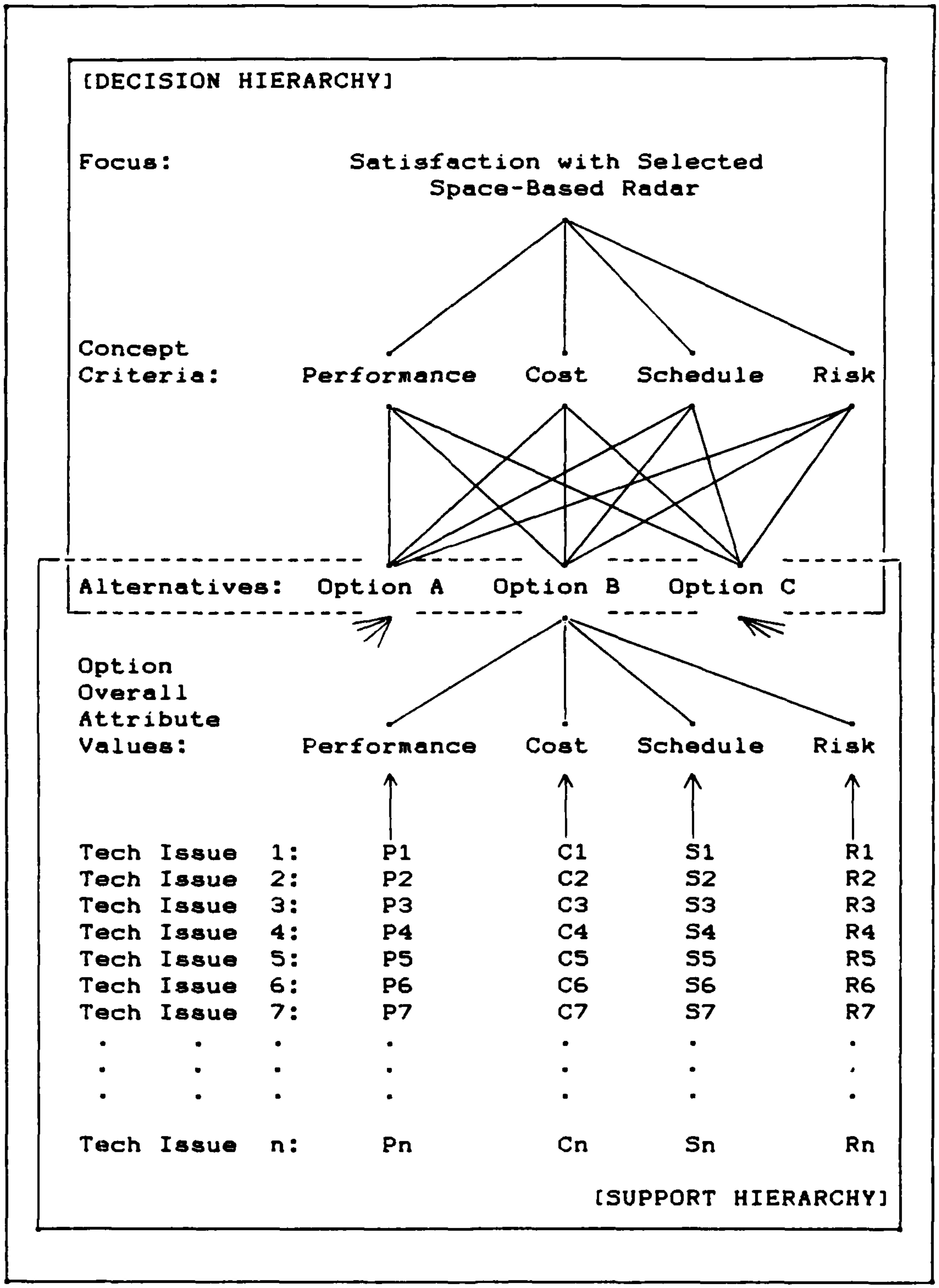


Figure 10: Functional Interaction Between Hierarchies

the collective assessment of technology issues through the support hierarchy provides an appreciation for a concept option's overall value. This value is measured in terms of performance, cost, schedule, and risk. Having characterized the options according to these attributes, the decision hierarchy, then, provides the structure for evaluation based on performance, cost, schedule, and risk as comparison criteria. AHP offers an appropriate means for this comparison.

At this point, the complete structure for the methodology is in place. As such, the first phase of the analytic hierarchy process, that of hierarchical decomposition, is also complete. Now the emphasis shifts to how the methodology functions to solicit values from the decision maker. In the analytic hierarchy process, this value assessment takes place through pairwise comparisons.

Comparative Judgments

Comparative judgment is the means by which the decision maker expresses preference in the analytic hierarchy process. In the space-based radar methodology, this process takes place in the decision hierarchy. All elements within a single level of the hierarchy are compared to each other, one-to-one, based on a single element from the next highest level. This comparison ultimately provides a value assessment used to prioritize all of the elements within a

single level. Thus, pairwise comparisons between elements within a single level is the means by which the decision maker attains priorities.

The expression of preferences through pairwise comparisons has several advantages. First, this process eliminates repetitive questioning by taking advantage of mathematical matrix manipulations to process responses. Secondly, the decision maker must compare only two items at a time. This reduces the complexity of multi-faceted problems. The notion here is that a decision maker can more easily establish values in the more limited, pairwise manner. Finally, the entire hierarchy need not be evaluated by a single individual. While one group of decision makers may make pairwise comparisons involving the top two levels, a separate group of decision makers may carry out comparisons of any other two levels, depending upon their expertise.

The Governing Element. The key to the comparison is the governing element. The governing element provides the criterion upon which elements in subsequent levels are pairwise compared. The governing element which pertains to a given series of comparisons resides in the next higher level. As an example, suppose a decision maker wished to compare, in a pairwise manner, three concept options from the bottom level of the decision hierarchy. If the basis for the comparison is the risk criterion from the intermediate level, then risk would be the governing element.

The governing element must also have associated with it a contextual relationship. Once specified, the contextual relationship further clarifies the criterion upon which the pairwise comparison depends. In the case where risk is the governing element, the contextual relationship can be stated as: How does concept option X compare to concept option Y on the basis of minimizing risk? Similar contextual statements exist for performance, cost, and schedule. The corresponding relationships for this methodology bring out the desire to maximize performance, minimize cost, and minimize the timeframe to scheduled production.

Scale. An appropriate scale for making judgments enhances the value of making pairwise comparisons through the analytic hierarchy process. The scale for judgment used in this methodology is given by Saaty and is depicted in Table II (29:54). The definitions and explanations that accompany the nine point scale enhance its utility. Saaty provides extensive theoretical and mathematical justification for its appropriateness to pairwise comparisons in AHP (29:53-64).

Format. The format in presenting pairwise comparison in accordance with the AHP scale may vary. To obtain the necessary data from a decision maker, a question format offers the most straightforward method by which to solicit a response. This approach is taken for the surveys explained in the next chapter. Pairwise comparisons framed

Table II. AHP Comparison Scale (29:54)

Intensity	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over the other
5	Essential or strong importance	Experience and judgment strongly favor one criterion over the other
7	Very strong or demonstrated importance	A criterion is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed.

in the form of questions lead the decision maker through the repetitive process in a familiar and uncomplicated fashion. Unfortunately, such a format is not conducive to the mathematical operations required to process responses. At some point, a transition must be made to a matrix representation.

The matrix format provides a mathematically functional format that is easy to visualize. All of the elements that are being compared come from a single level of the hierarchy and serve as the indices for the rows and columns of the matrix. This yields a square matrix for every set of AHP comparisons. AHP rating entries are placed in the intersecting row-column locations of the matrix corresponding to the pairwise comparison in question. AHP rating values of "1" appear on the diagonal. The governing element with its contextual relationship directs all comparisons within a given matrix.

Calculations. Matrix calculations provide the means of solving for the priority vector. Every matrix will have a priority vector as a solution. Using positive reciprocal matrices reduces the required number of responses to arrive at this solution. Tedious repetition is avoided by using transitivity to complete matrix entries where possible. When all entries have been made, computing the principle eigenvector and normalizing the result yields the priority vector. The priority vector, then, specifies the relative weighting for the compared elements.

The next chapter will serve to demonstrate the pairwise comparison process through example. As discussed in the example, survey participants were asked to make comparisons between elements in the decision hierarchy based on the AHP scale. Pairwise comparisons, however, only satisfy the second step of AHP. One important step remains.

Synthesis of Priorities

To arrive at a final weighting of alternatives, all local priorities must be synthesized to reach a global ranking. This requires taking the priorities gained from pairwise comparisons of the intermediate level and combining them with the priorities gained from the pairwise comparisons of the bottom level of the decision hierarchy.

Matrix mathematics plays an important role in the final step by providing the transformation for synthesis. There are two inputs. One is the priority vector from the intermediate criteria; performance, cost, schedule, and risk. This yields a single column vector. The other is the collection of concept option priority vectors under each criteria heading. If the decision maker considers only three concept options, this second collection of vectors yields a three by four matrix. Matrix multiplication performed between the single column vector and the matrix gives an overall priority vector. This resultant vector specifies the rankings for the concept options under consideration.

Consistency

AHP's ability to provide a measure of consistency contributes to its value in supplying concept rankings. This consistency ratio measures the decision maker's consistency in making pairwise comparisons. It is through the

proportionality of the preferences that the decision maker indirectly provides this measurement (29:21).

The consistency ratio comes from a comparison between a calculated consistency index and a tabulated random index. The maximum eigenvector and the number of elements for a given matrix determine the consistency index, or inconsistency index as it is sometimes called. This consistency index is given by (29:21):

$$\frac{(\lambda_{max} - n)}{(n-1)} \tag{2}$$

where

λ_{max} = the maximum eigenvalue
n = order of the matrix

The random value is specified by the number of elements for a given matrix according to a random index table. The one used in this work was generated at Oak Ridge National Laboratory and shown in Table III (29:21). The ratio of the calculated consistency index over the random index yields the consistency ratio.

Good consistency provides an indication that the decision maker has not dramatically changed his values during the rating process. Analysts consider responses with consistency ratios of ten percent or less as being acceptable (29:21). In the event of higher values, the decision maker should be given an opportunity to revise the original judgments. This might require restructuring the way

Table III. Average Random Index (29:21)

Order of Matrix	Random Index
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

comparisons are made, the way the problem is presented, or both.

Summary

The methodology presented here takes full advantage of the three steps of AHP. Hierarchical decomposition, pairwise comparisons, and synthesis of priorities all support the methodology as it relates to the MSSTP process. An effective measure of consistency is an additional benefit of AHP that evolves from these divisions of AHP. Demonstrating the methodology will more fully detail the function that these three steps play in clarifying trade-offs

for the decision maker. The next chapter provides this necessary perspective.

V. Application of the Methodology to Selected Space-Based Radar Concepts

Introduction

This chapter demonstrates the space-based radar methodology presented in the previous chapters. Three concept options are developed to serve as representative systems of potential interest to military decision makers. All three systems reflect real world systems only to the extent required to effectively implement the methodology. The appropriateness of these systems to the air surveillance mission is hypothetical. The systems themselves bear no resemblance to any specific system under review at this time. They do, however, provide an excellent set of concept options for demonstrating the methodology.

Included are details of the solicitation process for determining engineering assessments and value preferences required to demonstrate the methodology for space-based radar trade-offs. Fundamental mathematical calculations in support of the methodology are developed with the aid of a BASIC computer program. Input data is of parametric form and extensive use is made of data provided through survey. The intent is to present the material in a form that will easily conform to the format most suitable to military decision makers and the operational environment in which they must ultimately function. Avenues for expansion are

clearly indicated where their presence will significantly enhance the value of the final decision.

Engineering Assessment

The iterative process outlined with the space-based radar methodology depends upon the decision maker's knowledge of selected concept options. Only an effective engineering assessment can furnish enough information about the potential systems to start the functional decision hierarchy in motion. The demonstration of this methodology begins with a description of three concept options and an authoritative engineering assessment, both structured in accordance with the suppcrt hierarchy.

Concept Options. Concept options selected for demonstrating the methodology reflect performance and design considerations discussed in Chapter 3. They possess qualities that are appropriate to future systems. In a sense, they represent a composite of some proposed approaches previously studied by reputable space technology firms. In these three concept options, distinctions are drawn mainly around physical appearance of the major subsystems. For example, antenna structure and feed design are easily recognizable outward signs of design variations.

The intent in designating three concept options is only for the purpose of demonstrating the interaction of elements within the decision and support hierarchies to

support this methodology. In reality, the descriptions of each concept option must far exceed what is presented here. Detailed design and performance factors from every technology requirement under every technology discipline must be present. This analysis presents only a representative number of the technology disciplines with their associated technology issues. The process, however, does not change with the addition of further issues.

The concept options used in demonstrating this methodology follow. To aid the reader, included with each concept option is a brief explanation of some possible subsystem similarities with other existing or proposed systems.

Concept Option A. The first concept option is a corporate-fed phased array with a rigid fold-out panel type antenna. The deployment concept included in this design is an outgrowth of the type of technology employed in SEASAT by Ball Aerospace (35:33-36). This technology also appears in the designs of the Shuttle Imaging Radar (SIR)-A and SIR-B follow-ons to SEASAT (26d:4-16; 35:36).

Concept Option B. The next concept option is a space-fed phased array with a window shade roll-up type antenna. This antenna configuration stems from a concept considered by Grumman Aerospace Corporation which uses a three-layer membrane in the array structure (26d:4-16).

Concept Option C. The final concept option is a space-fed phased array with a wire wheel fold-up type antenna. This antenna configuration resembles the deployable

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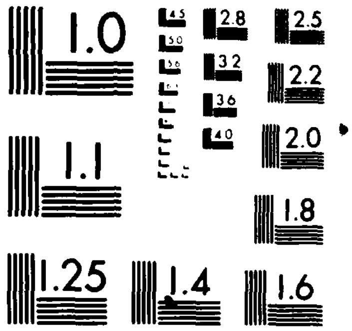

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structure at one point envisioned by Grumman Aerospace Corporation (18:11; 26d:4-12). The principle of operation is that of the space-fed lens phased array mentioned in Chapter 3.

Technology Issue Survey. Technology experts from an American Institute of Aeronautics and Astronautics (AIAA) space-based radar conference sponsored by STC characterized the concept options for this exercise. While attending the three day conference, each received a survey in connection with this thesis effort. This technology issue survey appears in Appendix A. The survey requested that each participant comment on technology issues associated with the three concept options. The survey further requested that they characterize the issues according to performance, cost, schedule, and risk using the rating scales provided in the survey. The rating scales parallel measures of performance, cost, schedule, and risk presently included in the MSSTP.

Purpose. The technology issue survey attempts to simulate the function of the support hierarchy in the overall methodology. The survey solicits information to contribute to the decision maker's understanding of the concept options. In its present form, however, the survey does not provide a fully exhaustive assessment. It only partially completes the requirement to characterize concept options. This is because existing details for potential concept options are still unclear at this point in time.

The author, therefore, played the role of the technologist to define concept options. This initiative was necessary to provide a hint of the performance and design concerns to start the technology issue evaluation. In reality, this is an iterative process which requires coordination between operators, technologists, and decision makers. One product of such an iteration is the further clarification of point designs for entry into this methodology.

The technology issue survey provides for this example what the MSSTP would supply in the overall methodology. The panel of experts assembled at the Air Force Space Technology Center function as the technology forecasters for the MSSTP (42). In doing so, these experts characterize the potential technology issues and requirements that apply to space-based radar concepts. The MSSTP, then, functions as the source document for information on technology issues. The survey captures the essence of this information to provide a timely demonstration of the methodology presented here.

Results. In performing the function of the support hierarchy, the survey then provides a characterization of the concept options. Like the structure for the support hierarchy described in Chapter 3, the survey depends upon technology issues. AIAA panel participants characterized concept options according to MSSTP technology issues within their own area of expertise. Intermediate results appear in Appendix B. The totals from the survey

Table IV. Summary of Technology Issue Survey Results

	Option A	Option B	Option C
Performance	133	143	150
Cost	34.7	38.8	40.6
Schedule	27.0	32.3	35.5
Risk	52.0	58.2	61.2

for option attributes of performance, cost, schedule, and risk are shown in Table IV. This data is open for interpretation by the decision maker to determine where the significant differences between concept options lie. The totals only give a relative appreciation of the strengths and weaknesses for each option by attribute.

The performance rating, in particular, provides an insight into how interpretations of the results may vary. In the example presented here, the six characteristics of performance were equally weighted. An expanded definition of these characteristics according to the MSSTP appears in Table V (28:3-11). Coverage, capacity, quality, timeliness, availability, and survivability were considered equally important in terms of their individual contribution to overall performance. Depending on the operational scenario, the equality assumed here may not be justified. A military decision maker may value capacity or quality more than coverage. For this reason, an expansion of

Table V. MSSTP Performance Parameters (28:3-11)

<u>Coverage</u>: Geographical boundaries over which the functions must be performed.
<u>Capacity</u>: The number of units served, detected, identified, tracked, etc. The number of messages, units, or bits transmitted or received per second.
<u>Quality</u>: Quantitative measures of the distinguishing attributes such as location accuracy, probability of detection, false alarm rate, probability of correct message receipt, track accuracy, probability of kill, etc.
<u>Timeliness</u>: Allowable system time delays or response times such as allowable time from event detection to message transmission of event detection.
<u>Availability</u>: Percentage of time the system must be in position and able to accomplish the assigned task.
<u>Survivability</u>: Endurance requirements imposed by the military mission or task. Specified in terms of the duration of time (minutes, hours, days, years) a function must be available to accomplish the associated task.

levels within the overall methodology to include a sublevel below performance in the decision hierarchy may be appropriate.

<u>Interpretation</u>. The support hierarchy, as represented in the technology survey, allows for the transition into the decision hierarchy. Based on the results of the technology issue survey, the decision maker can make certain deductions. The decision maker uses the raw data provided by the support hierarchy to compare concept options by applying the AHP rating scale. Granted, not all

decision makers will draw the same conclusions. Interpretations may depend on the format used to display the support data. Individual perceptions of scale and relative magnitude for the representative data may also vary. Even so, the methodology lends itself to easy discussion of the data to resolve disagreement.

For the purpose of demonstrating this methodology, the author assigned the AHP ratings in making the pairwise comparisons of concept options. These comparisons were based on an interpretation of the data which was gained from the support hierarchy as shown in Table IV. Rating according to the AHP scale in this manner satisfies the requirement to compare elements from the bottom level of the decision hierarchy according to intermediate level elements. Table VI shows the comparisons and the corresponding intensities that were deduced from the data for use in this demonstration. The matrices that arise from these comparisons appear in Appendix C. The BASIC program listing shown in Appendix F is the means used to arrive at the results indicated beside each matrix.

Notice that each series of comparisons under performance, cost, schedule, and risk has a priority vector. When assembled together, all priority vectors form a three by four element rectangular matrix as shown in Table VII. The matrix of Table VII, therefore, summarizes the intermediate results gained from comparisons of the options based on criteria elements from the decision hierarchy.

Table VI. AHP Pairwise Comparisons of Options

Pairwise comparisons based on performance:

Options	AHP Intensity
A vs B	1/5
A vs C	1/7
B vs C	1/4

Pairwise comparisons based on cost:

Options	AHP Intensity
A vs B	4
A vs C	5
B vs C	2

Pairwise comparisons based on schedule:

Options	AHP Intensity
A vs B	3
A vs C	5
B vs C	3

Pairwise comparisons based on risk:

Options	AHP Intensity
A vs B	5
A vs C	7
B vs C	3

Table VII. Concept Option Priority Vectors

	Performance	Cost	Schedule	Risk
Option A	.0691	.6833	.6369	.7306
Option B	.2437	.1998	.2582	.1883
Option C	.6870	.1168	.1047	.0809

The next step of the rating process requires a comparison of elements from the intermediate level of the decision hierarchy, level two, in relation to the focus, level one. The question that such a comparison answers is: how do overall performance, cost, schedule, and risk compare on the basis of their importance in satisfying the requirement for effective SBR air surveillance and tracking? Clearly, this answer depends upon the values of a particular decision maker.

Establishing Value Preferences

The panel members from the systems subgroup at the AIAA conference were given an additional survey. This value assessment survey asked each participant to decide on the relative importance of achieving optimum performance, minimizing system cost, meeting a demanding time schedule for operational capability, and producing a system that is of low overall risk. In completing this survey, shown in Appendix D, each person was providing opinions as the acting decision maker. As a decision maker, the panel members made pairwise comparisons that could be used as an input for the intermediate level of the decision hierarchy.

Value Assessment Survey. The value assessment survey provides feedback on the decision maker's feeling for the importance of performance, cost, schedule, and risk. When this response is processed by applying AHP, the result

Table VIII. Value Assessment Survey Responses

Evaluation	AHP Intensity
Performance over Cost	3
Performance over Schedule	3
Performance equivalent to Risk	1
Cost over Schedule	4
Cost equivalent to Risk	1
Risk over Schedule	4

is a priority vector for level two of the decision hierarchy. This gives the weightings for the four criteria based on the rater's judgment. Like the calculations for comparisons between concept options, the BASIC computer program listing shown in Appendix F was the means used to arrive at these results.

Results. Selecting the decision maker with the best consistency index provides a good source of data for continued demonstration of this methodology. The consistency index, as discussed in the previous chapter, provides a measure of how consistent the rater is among all of the pairwise responses. Lower percentages show higher consistency. The lowest attainable consistency index from all of the respondents, the value of .06, is used in this demonstration. The responses which lead to this value appear in Table VIII. The associated matrix and resultant priority

Table IX. Weightings for Intermediate Criteria

Performance	.3879
Cost	.2344
Schedule	.0816
Risk	.2959

vector appear in Appendix E. Finally, the weightings for all elements of the intermediate level of the decision hierarchy are summarized in Table IX. This priority vector specifies performance, risk, cost, and schedule as the order of importance in this example.

At this point, all pairwise comparisons are complete. The priority vector for level two of the decision hierarchy comes from the selected value assessment survey respondent. Additionally, the priority vectors from level three with respect to level two came from the technology issue surveys. Only the final synthesis remains.

The Final Solution

The final priority vector is an outcome of the analytic hierarchy process as it is applied to this methodology. This solution vector identifies the relative weights for the three concept options. The vector and matrix that are multiplied together to form the solution vector come from results previously depicted in Table VII and Table IX.

Table X. Element Weightings for the Decision Hierarchy

	Performance (.3879)	Cost (.2344)	Schedule (.0816)	Risk (.2959)
Option A	.0691	.6833	.6369	.7306
Option B	.2437	.1998	.2582	.1883
Option C	.6870	.1168	.1047	.0809

Table X displays these results in a format that combines all of the individual priority vectors. This shows the relative weightings for all elements of the decision hierarchy. The calculations using matrix mathematics are simple, but tedious. Rather than manually perform the calculations, a computer program offers a faster and more efficient approach.

The computer program for this operation is listed in Appendix F. The inputs to this user-friendly program come from the survey results. The participant need only provide the rating scale values and the number of elements in each hierarchy level to proceed with the evaluation of concept options. In the case of this methodology, the rated values come from Table X. The number of elements in the decision hierarchy are one, four, and three for the focus, intermediate, and bottom levels. Finally, the program establishes

Table XI. Final Results

Option A	-	.4552
Option B	-	.2182
Option C	-	.3264

the overall preferences for the three concept options as shown in Table XI.

The results indicate that Option A is the most preferred of the three options considered. Option C and Option B rank second and third, respectively. The outcome is not surprising when one recognizes the trade-offs of performance with the other attributes. As is often the case, with increased system performance comes corresponding increases in system cost, schedule, and risk. While Option A ranks lowest in terms of performance, as shown in Table IV, it also has the lowest cost, schedule, and risk. On the other hand, Option C possesses the highest values for all of the attributes. Option B occupies the middle ground. Only a commitment from the decision maker can resolve the trade-offs to establish Option A as the preferred solution.

Through the pairwise comparisons of this space systems methodology, the decision maker is able to arrive at the relative weights that determine the final priority. The decision maker internalizes the relative importance of judgment criteria as a value system and expresses those values as preferences. In this example, synthesis through

AHP reveals that the decision maker prefers Option A. Consistency is good as indicated by a consistency ratio of .06 for the entire hierarchy.

Comments

The demonstration presented here represents the entire decision process on a small scale. In practice, many more technology disciplines influence the final outcome. Furthermore, the number of actors in this process far exceeds the number consulted in the few surveys used for the SBR example.

The interactions presented in this methodology bridge the gap between mission requirements and the evolving technologies that support operational needs. Figure 11 illustrates the manner in which these interactions combine to support the decision process for space systems planning. At the outset, planners recognize air vehicle detection and tracking as a legitimate support mission for the combat mission of strategic defense. From this point, the illustration shows how considerations borne out of a specific operational scenario generate performance requirements that, in turn, give rise to a concept need. Space-based radar appears as one particularly viable space system concept that offers a means to meet this need through the application of advanced technologies. As defined by the methodology, review of concept options is, then, necessary

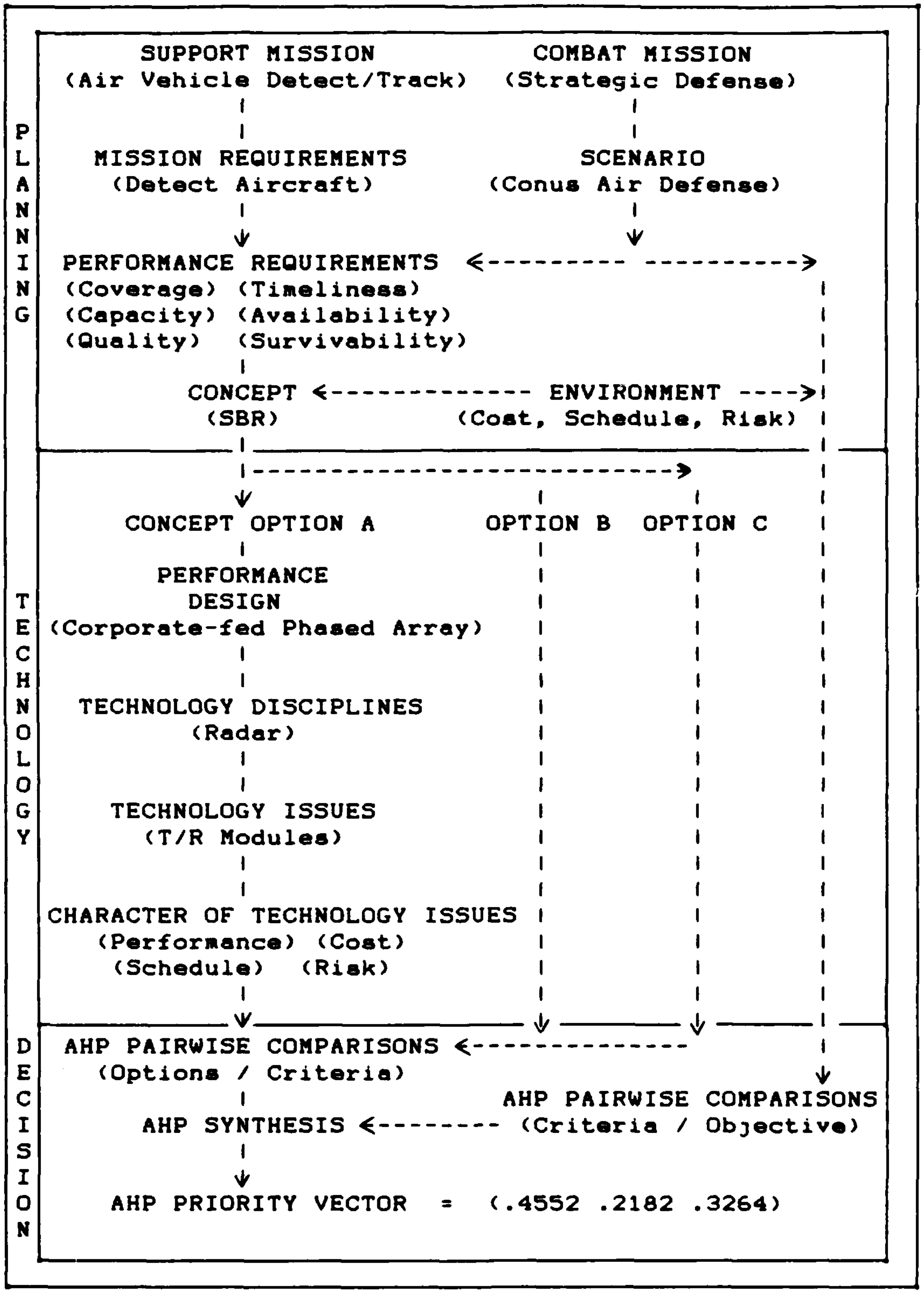

Figure 11. Methodology for Assessing Technology Trade-offs

to select the most acceptable alternative.

The capability of decision makers to make this choice hinges on their understanding of the scenario and their ability to make trade-offs. The degree of importance attributed to each aspect of performance is highly scenario dependent. Furthermore, performance, in reality, is only one concern in meeting the demands imposed by the scenario. Constraints of cost, schedule, and risk that arise from the social and political environments place additional burdens on decision makers. Thus, the posturing of forces, level of conflict, or perceived intentions of governments enter into the process by changing the manner in which the decision maker views both the operational scenario and the external environment.

The analytic hierarchy process, as presented in this methodology, incorporates all of the necessary considerations that support *effective* decision making. AHP is flexible enough to account for subjective assessments. Those assessments combined with knowledge of contributing technologies make realistic trade-offs possible. As Figure 11 shows, it is AHP that ultimately links the mission planning process with the technology structure to establish a clear sense of priority for the decision maker.

The interactions between various actors that influence the decision process for space systems planning are also particularly evident from Figure 11. The depiction summarizes the influences of the planning, the technology

forecasting, and the decision making functions that support effective decisions. Visualizing the linkages between actors facilitates the interchange of ideas across these functional lines. The methodology presented here provides this perspective and, thus, allows the decision maker to better understand the dynamic and iterative nature of the decision process. This understanding, in turn, gives an appreciation of how to arrive at an initial appraisal of concept options.

The space-based radar example serves to demonstrate how this methodology can provide such a well documented approach to decision making. Even though the space-based radar issues are varied and complex, the process presented here is straightforward and easy to implement. Two concept options can be traded off directly based on the technology issues making up their associated subsystems. The structure inherent in such a methodology provides insight at both the system and subsystem levels. Finally, it is important to recognize that concepts other than space-based radar can also benefit from this methodology due to its systems engineering basis.

VI. Conclusions and Recommendations

Conclusions

The methodology presented in this work consolidates systems engineering, operations research, and the MSSTP into a working network for decision making. It allows the decision maker to prioritize concept options based on expert engineering assessments and critical personal judgments. In doing so, this approach offers simplicity, flexibility, and realism.

It is the division of the MSSTP process into the decision and support hierarchies that provides the foundation for such a comprehensive approach. This dual structure within the methodology reveals the interactions that complicate the decision process. Ultimately, technology issues can be related to technology concepts through a structure that fosters clear trade-offs between concept options.

The analytic hierarchy process provides the means to perform these trade-offs. This management tool allows the decision maker to fully exploit the hierarchical development in order to express the relative worth of concept options. The manner in which AHP incorporates both technology assessments and subjective judgments as reasonable evaluators of overall system performance adds to its utility. This adaptation of AHP capitalizes on the experience that knowledgeable managers and engineers contribute to the

decision process. Whether through survey or through the documentation provided by the MSSTP, the methodology presented here recognizes the value of the experts' opinions in making space system trade-offs. AHP highlights the unique contributions offered by these different actors and supplies the means to quantify their input.

Having synthesized these inputs, the methodology's structure helps the decision maker to communicate the justification for trade-off decisions. This environment for open communication leads to the consensus necessary for a coordinated development effort. Since the structure of this methodology is straightforward, the path to a decision is more evident to all who participate. Consequently, decision makers can resolve differences that might otherwise impede the decision process. The ability to communicate and resolve issues is an important feature for a methodology that must span multiple disciplines in the process of conveying the mission objectives, the alternative designs, and the technology issues. The logic for a chosen course of action is subject to countless reviews in the effort to both obtain the best solution and reach agreement in the process. This approach allows a decision maker to trace through the decision process to expose the justification for established preferences.

The space-based radar example demonstrates that, indeed, the theory behind this approach has a meaningful application to space systems. This proposed space concept

brings to light the multiple competing factors that influence space system design and employment in support of the air surveillance mission. The need for a structure to outline the issues is apparent. This methodology proves capable of dealing with these multiple issues in a manner that interrelates performance, design, and technology issues within the basic technology format of the MSSTP.

Weighted measures of performance, cost, schedule and risk within the methodology serve as reminders of the realities that actually drive management decisions. The methodology takes into account the variable importance of these criteria in allowing for subjective opinions from decision makers. While their relative weights may change based on how the operational scenario motivates those subjective opinions, the decision process outlined by the methodology remains the same.

One of the most significant observations to be made from this work is the need to recognize the importance of the MSSTP in the overall decision process. The MSSTP's value is not solely due to its funding recommendations or technology projections. It is an essential source of data for making trade-off decisions. The MSSTP serves a very functional purpose in supporting the decision maker through its ability to characterize space system concepts at their most fundamental level.

Throughout this work, the need for an easily understood approach has always been at the forefront. An overly

complex methodology provides no utility if planners and analysts cannot communicate the means of reaching the result. The methodology presented here offers a common ground for understanding the decision process and a starting point for further research. It serves to model the decision process used to support military operations by capturing the factors that govern the influx of technology to space systems.

Recommendations

The recommendations that follow provide insight into where and how further development can enhance the principles set forth in this thesis. These suggestions stem from an appreciation of the broad nature of the MSSTP. At the same time, recommendations acknowledge the need to streamline management techniques through well-structured and clearly defined guidelines for characterizing potential space systems.

Definition of Concept Options. The further division of concepts into concept options should be increasingly emphasized in upcoming versions of the MSSTP. Concept options are a natural product of the iterations borne out of the MSSTP process. Acknowledging their existence up front will narrow the field of unique concepts within the MSSTP. This admission will prevent duplication of effort in describing concepts while still retaining the

flexibility to recognize alternative technologies as viable solutions.

Concept options also lend realism to the decision process by providing a foundation for characterizing technology issues. This quality is a key feature contained in the methodology. The increased detail afforded by the concept option enables technologists to provide a more accurate appraisal of technology issues. More accurate assessments, in turn, lead to a clearer understanding of where the most important trade-offs lie. This helps to focus the pertinent issues for the decision maker.

Finally, division into concept options supports engineering trade-offs by allowing a greater appreciation for complementary and parallel technology issues. While a comparison of completely separate concepts based on complementary and parallel issues may be exceptionally limited, comparisons of concept options under a single concept generally will expose stronger relationships. This result is a consequence of the greater appreciation gained from recognizing the commonalities and differences among concept options under a single concept.

Expansion of Hierarchical Levels. Consideration should be given to expanding the intermediate level criteria into sublevels. Performance and risk appear as two likely criteria that are particularly worthy of such consideration. Expanding the number of levels better defines the relevant concerns of decision makers. This expansion,

thereby, provides a greater granularity or sensitivity in making trade-off decisions.

An excellent point of departure would be the expansion of risk along the lines of criticality and pervasiveness as emphasized by Dr. Stephen Book of Aerospace Corporation (4; 5; 6; 7). In the case of criticality, this breakdown defines a measure of risk according to the number of critical technology issues under a particular concept option (4; 5). For pervasiveness, the division defines a measure of risk according to the number of technology issues under a particular concept option that show a great degree of commonality with other concepts (4; 5). Both criticality and pervasiveness would comprise a single sublevel of the hierarchy under risk.

The division of risk into criticality and pervasiveness further clarifies issues for the decision maker. Each quality would receive an appropriate weighting in the decision hierarchy based on pairwise comparisons through AHP. Functionally, the synthesis step of AHP provides the means for incorporating the associated weights into the final priority vector.

The suggested breakdown of performance which already exists within the MSSTP offers a second means of expanding the hierarchy. The six items of coverage, quality, capacity, timeliness, availability, and survivability represent an excellent choice for elements within a performance sublevel. Each of these should be incorporated into the

hierarchy for pairwise comparisons to obtain AHP weightings. The resultant AHP ratings would reflect preferences for aspects of performance that more accurately model operational concerns.

As an aside, there are also provisions within this methodology for including additional elements within a single level of the hierarchy. Survivability, reliability, and maintainability represent possible candidates. However, this recommendation comes with a note of caution. Although adding another element to any level is possible, all elements within a single level must possess a relative degree of importance within the same order of magnitude. This requirement serves as a check for whether such an addition is appropriate.

Development of a Decision Support System. A comprehensive decision support system (DSS) based on an expansion of this methodology should be developed to enhance the MSSTP process. This development would extend the capabilities of the MSSTP data base, provide a manageable interface with the many MSSTP participants, and function as an effective decision making tool for Air Force leaders.

Computer implementation offers the most efficient way to apply this methodology. The AFSTC currently maintains an extensive data base used to characterize technology issues according to the format of this methodology (44; 45). Linking this data base with a decision methodology such as the one proposed here would provide the beginnings for a

powerful decision support system. With the advent of the microcomputer in Air Force offices, programs based on microcomputer applications provide a strong foundation for decision support systems. The methodology presented here should be included in the model base for a DSS that exploits the virtues of a microcomputer interface with the MSSTP data base.

An initial effort to demonstrate the feasibility of applying this methodology to a microcomputer-based decision support system is already in progress (36). 1Lt Bruce Schinelli from the Air Force Institute of Technology has implemented portions of this methodology to demonstrate how the methodology relates to DSS management objectives (36). His interactive microcomputer program reveals the improved user interface that a DSS provides. Such an application serves to benefit decision makers in their attempt to obtain information and convey responses to other participants in the decision process.

In addition to the improved user interface, a DSS promises to shorten the MSSTP cycle. Technologists can provide timely responses to concept options detailed within the data base based on their perceptions of the technology issues from their own field of expertise. Networking can provide a means for intradisciplinary exchange on critical technologies. Group synthesis is accelerated and efforts to characterize technology issues promise to be more effective.

Finally, Air Force leaders can better discern the multiple issues addressed in this methodology through a DSS application. The decision making arena for space systems is a complex environment that requires a structural approach to problem solving. The space systems methodology shown here provides this necessary structure. A decision support system reinforces the structure and adds understanding to the overall approach.

Appendix A: Space-Based Radar Technology Issue Survey

To AIAA Space-Based Surveillance Panel Participants

Dear __________,

I would like to request your assistance in completing the attached space-based radar technology issue survey. This survey supports a thesis effort within the Operational Sciences Department of the Air Force Institute of Technology. The thesis effort complements work sponsored by the Air Force Space Technology Center.

Your experience with technology development related to space-based radar makes your input especially relevant. The insight that you provide will be an important contribution in demonstrating a decision methodology for space systems.

Please take a few minutes to read the instructions and complete the survey. Should you have any problems in completing the survey, I am available to answer questions and can be contacted at the phone number listed below.

Thank you.

John E. Puffenbarger, Capt, USAF
Graduate Student for Space Operations, AFIT

Local Phone Number ____________

Space-based Radar Technology Issue Survey

In this survey, you are asked to identify technology issues associated with three space-based radar options. All options perform the mission of detection and tracking of air-breathing targets from space.

Admittedly, the design descriptions and performance specifications of these three options are vague. Use your own judgment to make design assumptions where you feel they are needed to confirm or eliminate a potential technology issue from your list. For example, you may choose to select L- or S-band as a frequency for a particular concept option.

The intent of this survey is to distinquish between options by identifying technology issues under each option and characterizing those technology issues. Characterize the technology issues so as to highlight the degree of cost, schedule, or risk associated with each technology issue.

The same technology issues will not necessarily be common to all options. However, for those issues that do appear in more than one concept option, try to distinguish the factor or factors that may alter the character of those issues under different options.

To evaluate performance, you are asked to rate each option according to six criteria. The six criteria for making these ratings are listed in a table provided on the last page. A rating scale accompanies this performance table. Use the concept description, your previous assumptions, and your technology issue breakdown to help in rating.

To aid you in your efforts, a list of current MSSTP technology issues is attached. If you feel that there is a need to clarify some aspect of a technology issue for a concept option, please write in your comments.

The three concept options for this survey are:

Option A: Corporate-fed phased array with rigid fold-up panel type antenna.

Option B: Space-fed phased array with window shade roll-up type antenna.

Option C: Space-fed phased array with wire wheel fold-up type antenna.

Place the number of the technology issue that you feel pertains to each option in the blank provided. Also characterize each technology issue within each option according to cost, schedule, and risk. Base your ratings on the scale provided. Once you have completed this portion, proceed on to rate performance on the last page.

Rating Scale

Cost:	1 (low)		2 (medium)		3 (high)
Schedule:	1 (near term) (before 1995)		2 (intermediate) (1995-2000)		3 (far term) (after 2000)
Risk:	1 (very low)	2 (low)	3 (medium)	4 (high)	5 (very high)

CONCEPT OPTION A: Corporate-fed phased array with rigid fold-up panel type antenna.

Assumptions: ____

____

____

Technology Issue	C	S	R
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___
_________	___	___	___

Characterization: C, S, R

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____

____

____

CONCEPT OPTION B: Space-fed phased array with window shade roll-up type antenna.

Assumptions: ____

____

____

Technology Issue	Characterization C	S	R
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___

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CONCEPT OPTION C: Space-fed phased array with wire wheel fold-up type antenna.

Assumptions: ____

____

____

Technology Issue	Characterization C	S	R
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___
________	___	___	___

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Performance Rating Scale

Serious shortcoming in performance	=	1
Lower intermediate level of performance	=	2
Meets acceptable level of performance	=	3
Higher intermediate level of performance	=	4
Strongly exceeds performance requirements	=	5

	Option A	Option B	Option C
Coverage (area of detection)	----	----	----
Capacity (number of targets)	----	----	----
Quality (accuracy in altitude, speed or heading)	----	----	----
Timeliness (response time)	----	----	----
Availability (percentage of time fully mission capable)	----	----	----
Survivability (hardening, ECCM, and anti-jam features)	----	----	----

Autonomy

(1) Autonomous Satellite Maintenance (ASM) - Involves routine maintenance functions, such as thermal control, battery charging and reconditioning, and solar array pointing, as well as the detection and correction of on-board faults.

(2) Expert Systems Applications - The application of artificial intelligence systems to critical satellite data.

(3) Self-Organizing Failure Characterization and Prediction - Develop algorithms for autonomous assessment of critical satellite data and identification of anomalies and faults.

Communication

(4) A/J Signal Processing - Develop an efficient signal processing capability to satisfy future MILSATCOM requirements (high through-put/low weight and power).

(5) EHF Low Noise Receiver - Develop an advanced receiver at 44 GHz using multiple approaches to provide improved noise figure, dynamic-range, small size/weight/power and reliability.

(6) EHF Nulling Antenna - Developing jam-resistant nulling antennas to operate at EHF frequencies which are lightweight, low power consuming and launchable.

(7) EHF Receiver Antenna - Develop 30/44 GHz multiple beam antennas which are high gain, lightweight and low power consuming.

(8) Medium/High Rate Laser Crosslinks - Develop 100 Mbps/56bps data rate capability, which includes developing the laser sources, laser receivers/detectors, acquisition and tracking systems and networking capabilities.

(9) Optical Processing - Develop high modulation bandwidth, spatial light modular grids, low noise optical detector grids and low power, high intensity light source arrays and grids.

(10) SHF Power Amplifier Module - Develop an advanced (higher power/efficiency) monolithic power module for a 20 GHz active aperture antenna (2.5 watts saturated/1.5 watts linear at 20% efficiency).

(11) SHF Solid State Power Amplifier - Develop an advanced 20 GHz power amplifier (40 watts CW, 30 dB gain, 2.5 GHz BW).

(12) SHF Transmit Antenna - Develop 20 GHz solid-state, time trapped, beam phased array antennas for space use.

(13) Signal Processing Components - Develop the communications-peculiar hardware to implement a rad-hard advanced signal processor.

(14) 60 GHz Low Noise Receivers - Develop an advanced 60 GHz, low noise "front end" to include a fixed-LO, wideband mixer down converter and a microwave FET IF amplifier, as well as a 60 GHz FET LNA.

(15) 60 GHz Solid State Power Amplifier - Develop a complete 10 watt, 60 GHz transmitter at high efficiency (10 watts CW, 30 dB gain, 12-15% efficiency).

Environment

(16) Ionospheric Propagation Effects - Improve the understanding and prediction of ionospheric scintillation, particularly nuclear induced, in order to assist the design and operation of communication and radar systems.

(17) IR Background/Radiation - Reduce the effects of earth/cloud clutter, atmospheric emission and celestial sources on IR sensors.

(18) Low Level Atmosphere - Reduce the effects of clouds and rain on electro-optic and communication systems. Reduce the effects of wind and density on new reentry systems.

(19) Neutral Upper Atmosphere - This technology issue addresses the programs required to improve measurements and predictive capabilities with accuracies greater than 90% for atmospheric density and other atmospheric parameters. Specifically, develop improved models of the lower thermosphere for low orbit satellites and the mesosphere for ROTVs. Density is specified by global models at altitudes between 50 and 150 km.

(20) Satellite Radiation Environment - Develop improved models of the solar, cosmic ray, trapped and nuclear sources of radiation to aid spacecraft design and radiation mitigation techniques.

(21) UV Radiation - Address the spectral region ranging from 50 to 4000 A. Examine the deficiency in coverage of geophysical variabilities, celestial backgrounds, global variability of emissions, spatial and spectral resolutions, and solar variabilities.

Electro-Optics

(22) Algorithms/Processing - Develop radiation hardened systems using signal processing techniques as well as background suppression algorithms.

(23) Image Control - Develop detection and tracking algorithms, jitter and drift models and smear compensation techniques.

(24) IR Focal Planes - Develop detectors, detector arrays, integral focal planes and tunable filters.

(25) Telescopes and Optics - Develop large, laser hardened and contamination-free optics.

Guidance, Navigation and Control

(26) Acquisition, Pointing and Tracking - Develop improved capabilities for satellites and their payloads to acquire and track targets and, in the case of weapons applications, point accurately at targets.

(27) Advanced Survivable GNC System - Develop the capability to bring satellites on-line after long term in-orbit storage; develop a quick response deployment of satellites with minimal launch checkout.

(28) Attitude Determination - Develop a wide field of view (8 degrees) star sensor with an accuracy of .1-2 arc-sec. Improve the accuracy of the star catalog.

(29) Autonomous Navigation - Develop the capability for autonomous attitude determination and navigation to include star sensor development, nonconventional gyro development, and update of the star catalog.

(30) AVCS Maintenance - Develop a data base with respect to autonomy requirements for momentum control, stationkeeping control and redundancy management. Obtain experience through actual subsystem design, ground demonstration and flight test.

(31) Large Space Structure Control - Develop the technology to actively control space based structures, and initiate an integrated space/ground technology program.

Information Processing

(32) A/D Converters - Develop fast, radiation hard, space deployable A/D converters.

(33) Data Processing - Develop small, high speed data processors incorporating fault tolerance and high reliability in order to support requirements for extended autonomous operations.

(34) Hardened RAMs - Develop high speed, high density and low power random access memories which are immune to natural and nuclear radiation environments.

(35) Nonvolatile Memory - Develop a high density, low power and nonvolatile memory to protect semipermanent data (program memory, calibration constants, permanent data, etc.) during nuclear transients, power transients and faults.

(36) Signal Processing - Develop high speed signal processing capabilities to provide on-board data reduction of high capability sensor data streams.

(37) Software/Algorithms - Develop improved techniques for software development, verification and maintenance to provide reliable and efficient software. Develop more efficient and higher performance algorithms for on-board processing functions.

Man-in-Space

(38) Biological Radiation Protection - Investigate the effect of background galactic cosmic rays, trapped particle fluxes in the mangetospher[and solar particle events as they affect the man in the system. Spacecraft charging and arc discharging will also be investigated.

(39) EVA/Life Support - Because the Air Force missions may differ substantially from NASA's, the EVA equipment required to support such missions must be developed either in parallel or independently of NASA's efforts.

(40) Manned Military Functions - Characterize man's capabilities (dexterity, visual acuity, etc.) in space in support of military missions. Develop design methodologies and performance data base handbooks.

(41) Manned Performance Enhancement - Improve man's space adaptation, man-machine interfaces and voice control technologies, and develop active escape and rescue systems for space systems.

Manufacturing

(42) Composite Manufacture - Develop large area, and in some cases large quantity, advanced composite structures that have uniform properties. Develop controlled

manufacturing processes, coating processes and joining techniques.

(43) Electronics Production - Develop standard packaging, increased yield and radiation hardening processes for electronics packages. Improve T/R chip and module production.

(44) Flexible Automation - Investigate the problems associated with high volume, as well as low volume, production. Develop real time process verification of all production processes.

(45) Optics Production - Develop the Rapid Optical Fabrication Technology (ROFT) for new mirror materials, and expand conventional facilities to meet near term needs.

(46) Power Distribution - Develop: slip rings; power transmissions, such as cabling, shielding and interconnects; space assembly techniques; and large power distribution systems.

(47) Precision Machining - Develop closed loop control of tools, sharp and precise cutting tools, fixturing, high speed tools and control of tool and fixture vibration.

(48) Verification Assembly - Develop manipulator applications capabilities for orbital assembly and maintenance support.

Materials

(49) Adhesives/Seals/Sealants - Develop high temperature organic and ceramic adhesives, large area joining, nonautoclave cures, laser and nuclear hardened adhesives and cryogenic seals.

(50) Carbon-Carbon Hot Structures TPS Composites - Apply existing state-of-the-art technology and materials to develop thin gauge, lightweight, dimensionally stable carbon-carbon composites for space structures.

(51) C-C Survivable Structural Composites - Develop structural carbon-carbon composites, to include fiber and matrix development as well as characterization of the composites.

(52) Contamination - Develop material acceptance criteria. Understand surface and plume effects. Develop a data base and an accurate verifiable model. Develop active control measures. Develop low outgassing materials. Understand laser effects on materials.

(53) Electrical Coatings/Encapsulents - Develop coatings with low dielectric loss, good vibration damping and effective adhesion.

(54) Electrical Insulation Materials - Develop higher heat resistant materials for electrical insulation applications.

(55) Film Materials - Develop film materials for a 10-year life in a space environment. The materials are to be nuclear and laser hardened, with a high modulus and excellent conductivity. Applications for the film materials to include MLI, solar array substrates and conductive coatings.

(56) Metallic and Ceramic Hot Structures - Structures for earth-to-orbit application that are also highly survivable.

(57) Metal Matrix Composites - Development of metal matrix technology to maturity to bring it up to par with organic matrix technology. This includes materials development, analysis, design, NDE, joining, survivability testing, manufacturing, and demonstration.

(58) Organic Matrix Composite - This issue involves developing ordered polymer resins, high temperature matrices, low outgassing/outgassing control, manufacturing, damping characterization, thermoplastics, and demos.

(59) Printed Wiring Board Substrates - This issue includes the development of new materials for substrates, assembly, manufacturing, and computer aided design of substrates.

(60) Space Lubricants - Develop liquid and solid lubricants to survive future space environments. Develop improved storage and metering of liquid lubricants. Develop lubricant models. Improve hard coating for bearings.

(61) Vibration Damping Materials - Includes materials development for future needs and expected environments, characterization of the inherent damping of composite materials, and integrating and optimizing damping into active and passive control of space structures.

Propulsion

(62) Launch Vehicle Propulsion Performance - improvements in SSME engines, development of new higher thrust, high ISP, more reusable engines for future launch vehicles application.

(63) OTV Propulsion Life - Development of reusable OTV propulsion systems, improved turbine life, improved materials for combustion chambers, longer cryogenic storage, etc.

(64) OTV Propulsion Mass - OTV mass reduction provides greater payload-to-orbit capabilities for future transportation systems.

(65) OTV Propulsion Performance - Higher thrust, efficiency, and impulse levels as they relate to medium size propulsion systems (500-1500 lbf). Systems such as RL-10, PAM-D, IUS, etc.

(66) OTV Propulsion Survivability - Issues include radar and infrared exhaust plume signature characterization and propulsion system hardening against natural, nuclear and laser environment.

(67) SAT Propulsion Life - To achieve mission durations of ten years and longer and on orbit storage.

(68) SAT Propulsion Mass - Reducing propulsion system inert mass is another way to bring down overall satellite mass or allow for more mission payload.

(69) SAT Propulsion Performance - Improvements in ISP, efficiency and thrust through programs such as advanced propellant development, high chamber pressure and area ratio.

Power/Energy

(70) Advanced Survivable Solar Arrays - Develop photovoltaic designs using doped materials to create more efficient cells and concentrator structural designs to provide higher solar power output with better tolerance against directed energy weapon threats.

(71) Dynamic Isotope Power System - Develop a power source capable of delivering up to 10 kWe using the constant heat generated by isotopic element decay and converting the heat into electrical power by use of static or dynamic power conversion components resulting in a potentially more durable, compact power source to overall spacecraft survivability.

(72) Electrochemical Energy Storage - Develop innovative, scaled up energy storage technologies (i.e. batteries, fuel cells, flywheels), capable of very high depth of discharge for instantaneous power output demands in short duration applications.

(73) Power Conditioning - Develop lightweight power conditioning components to support surveillance concepts at medium voltage and current levels to prevent electrical discharge and prevent efficiency losses due to longer cable requirements.

(74) Solar Thermal Dynamic Power System - Develop a power source which uses concentrated sunlight to generate heat which drives rotating components for electrical conversion.

(75) 100 kw Nuclear Reactor - Perform trade studies for specific system designs. Perform a ground demo for a 25-50 kw system.

Radar

(76) L-Band, T/R Modules - Develop capability to produce large numbers of low power, high yield, high efficiency, small size modules.

(77) Low Sidelobe Antenna - Develop a low weight per unit area, low sidelobe (-10dBi far out), large size (up to 100m) 2-D electronic scan active phased array antenna with pattern control for adaptive nulling and clutter suppression.

(78) Main Beam Clutter Cancellation - Develop techniques for main beam clutter cancellation in the 1.2 GHz region.

(79) Radar Cross Section - Develop a comprehensive data base of high resolution imagery of tactical military vehicles and installations (to an accuracy of at least 1 dB).

(80) S-Band T/R Modules - Develop techniques to improve fabrication yield and minimize chip size for S-band modules.

(81) Sidelobe Cancellation/Adaptive Nulling - Develop techniques for phased array antennas to reach adaptive nulling levels of 40-53 dB.

(82) Target Classification/ID - Develop an operational ship and aircraft ID technique. Develop an automated image interpretation capability for parked aircraft, military installations, technical vehicles and space objects.

(83) X-Band T/R Modules - Develop techniques to improve fabrication yield and minimize chip size for X-band modules.

(84) 60 GHz T/R Modules - Develop capability to produce at high yield a large number of small size, low power, high efficiency modules.

Structures

(85) Deployable/Erectable Structures - This issue involves concepts, deployment dynamics, simulation, deployment devices, validation of devices, modular and system deployment, and nonlinear structures deployment.

(86) Fracture Mechanics - The material strength and fracture properties can be balanced so that a lightweight structure can be designed and fabricated with sufficient damage-tolerance for long life and safety.

(87) Structural/Control Interaction - Includes defining structures control problems, developing design methodology, and actual designs. Also addresses incorporating passive control (damping) of structures into active control systems and optimization to reduce the amount of active control.

(88) Structural Design/Analysis - This issue addresses design requirements, environmental, mechanical, and thermal load criteria, and acceptance criteria. It also includes optimization methods.

(89) Structural Materials - This issue includes the testing of materials for dimensional stability and damping characteristics in order to optimize design by integrating materials information into the design process.

(90) Structural Testing - Incorporates both ground and flight testing to better understand structure deployment, control, design, and verify analysis.

(91) Thermal Structures - This issue involves basic research, hot structures, and cryogenic tankage and would include testing, NDI, analysis, material development, joining, insulation, and life cycle.

Survivability

(92) Nuclear Effects Survivability - Develop hardening techniques to protect components, subsystems, and systems against effects derived from nuclear explosions. Includes methods to protect communication links and all segments of potential vulnerability to a nuclear effects threat.

(93) Particle Beam Survivability - Analyze methods to

protect components, subsystems and systems against broad threats posed by neutral particle beam.

(94) Satellite Laser Survivability - Explore, develop and test a variety of methods to protect components, subsystems, and total spacecraft from postulated laser threats.

Test and Evaluation

(95) Large Space Structures Test - To develop on-orbit deployment and restow mechanisms, assembly/disassembly techniques, EVA assist equipment, tools/aids as required to perform a large structure test in space utilizing the space shuttle.

(96) Laser Vulnerability Test - Laser threat simulation in a thermal vacuum environment will require improved delivery optics as well as diagnostic tools to monitor and confirm the actual threat level.

(97) Miss Distance Indicator - Although on-board miss distance measurement systems using numerous theories-of-operation exists, a technology need exists for the measurement of miss for directed energy systems.

(98) Particle Beam Vulnerability Testing - Simulation of the threat environment resulting from directed energy weapons will require extensive enabling technology development, currently judged to be more difficult than the first generation simulation of the nuclear and laser threat.

Thermal Control

(99) Coatings - Develop unique material with low absorption and high emissivity for more efficient thermal management of sensitive spacecraft components, such as electronic blackboxes and electro-optical sensors, while retaining the ability to dissipate excess heat at higher temperatures to handle increased power loads.

(100) Cryogenic Fluid Storage and Conditioning - Explore designs allowing long life storage of cryogenic fluids by minimizing natural boil off processes.

(101) Cryogenic Refrigerators - Develop a variety of technical approaches leading toward lower temperature operation of optical sensors which will result in longer lifetimes.

(102) Heat Rejection System - Develop technologies to provide minimum weight and area of heat dissipation, such

as innovative heat pipes operating at high temperature and film radiators using ferrofluids.

(103) High Heat Flux Methods - Evaluate, select, design and develop innovative ways to handle orders of magnitude fluctuation of thermal energy while maintaining equilibrium operation of highly sensitive subsystems with a given space platform.

(104) High Power Thermal Management - Examine optimum integrated methods to design efficient heat management of components and subsystems which must efficiently operate under a broad range of temperatures and wide range of power levels.

(105) Survivability Methods - Develop special coating materials capable of withstanding high heat fluxes postulated for future directed energy weapon threats.

(106) Thermal Protection - Develop methods of active cooling using coolant fluid(s) and advanced materials.

(107) Thermal Transport Devices - Develop more efficient transport devices to transfer heat from source.

Weapons

(108) Beam Control Accuracy - A subsystem technology that involves integrating advanced optical components, control systems, and precision lightweight structures.

(109) Excimer Power Scaling, Beam Quality - Technologies essential to scaling excimer lasers to high average power include laser cavity flow loop and gas conditioning; power conditioning and high-power, broad area electron guns; and optical resonators. In addition, stimulated Raman and Brilliouin scattering may be required to achieve near diffraction-limited beam quality.

(110) FEL Resonator - The free electron laser (FEL) resonator includes a high-efficiency oscillator, an E-beam injector and a high-gain amplifier with a pulsed optical train.

(111) HF/DF Power Scaling, Efficiency, Beam Quality - Extrapolation of current HF/DF technology at a particular efficiency and beam quality to higher beam power and brightness levels.

(112) Interceptor Development - The attempt to produce a lightweight projectile capable of withstanding high accelerations for both endoatmospheric and exoatmospheric applications.

(113) Interceptor Guidance - The ability of a projectile and its platform or interceptor to perform midcourse and terminal homing.

(114) Large Laser Optics - Optics including lightweight, high reflectivity 10-15 meter diameter mirrors capable of handling high flux loading from ground based or space based lasers.

Appendix B: Compiled Technology Issue Survey Responses

C = Cost   S = Schedule   R = Risk

Technology Issue by Discipline	Option A C	S	R	Option B C	S	R	Option C C	S	R
Environment									
16 Ionospheric Propagation Effects	1	1	2	1	1	2	1	1	2
34 Hardened RAMS	2	2	4	2	2	4	2	2	4
Information Processing									
36 Signal Processing	2.5	2	3	2.5	2	3.5	2.5	2	3.5
37 Software/ Algorithms	3	1	4	3	2	4	3	2	4
Manufacturing									
43 Electronics Production	2	1	3	2.5	2	3.5	2.5	2	3.5
44 Flexible Automation	2	1	3	2	2	3	2	2	3
Radar									
76 L-band T/R Modules	1.9	1.1	2.4	2.3	1.9	3.1	2.3	2	3.4
77 Low Sidelobe Antenna	2.5	1.5	3	2.7	1.8	3.3	2.8	2.3	3.8

		Option A			Option B			Option C		
		C	S	R	C	S	R	C	S	R
78	Main Beam Clutter Cancellation	1.8	1.5	3	1.7	1.7	3.3	2	3	4
79	Radar Cross Section	1	1	1	1	1	1	1	1	1
80	S-band T/R Modules	2.3	1.3	2.3	2.5	1.5	3	3	2	3
81	Sidelobe Cancellation /Adaptive Nulling	2.2	1.8	3.6	2.4	2	4	2.6	2.2	4.2
82	Target Classifi-cation/ID	1.3	1.3	2	1.3	1.3	2	1.3	1.3	2
Structures										
85	Deployable /Erectable Structures	2.2	1	2.2	2.4	1.6	3	2.6	2.2	3.8
Survivability										
92	Nuclear Effects	1	1	2	1	1	2	1	1	2
93	Particle Beam	1	1	2	1	1	2	1	1	2
94	Laser	1.5	2	3	2	2	3.5	2	2	3.5
Test and Evaluation										
95	Large Space Structures Test	1.5	1	2.5	2.5	1.5	3	3	1.5	3.5

	Option A			Option B			Option C		
	C	S	R	C	S	R	C	S	R
Thermal Control									
105 Survivability Methods	2	3	4	3	3	5	3	3	5
Totals	34.7	27.0	52.0	38.8	32.3	58.2	40.6	35.5	61.2
Mean Value	1.83	1.39	2.74	2.04	1.70	3.03	2.14	1.87	3.22
Stand Dev.	.584	.546	.809	.685	.504	.939	.748	.605	.999

The performance results in the following table reflect equal weightings for coverage, capacity, quality, timeliness, availability, and survivability. The entries for a respondent represents the sum of these factors for each concept option.

Table XII: Performance Results

Respondent	Option A	Option B	Option C
1	15	18	17
2	18	17	20
3	18	18	18
4	20	19	16
5	13	16	19
6	18	17	18
7	15	18	21
8	16	20	21
Performance totals of all respondents for each Option:	133	143	150

Appendix C: Comparison Matrices for Concept Options

The following matrices display the pairwise comparisons of concept options based on intermediate level criteria from the decision hierarchy. The governing element appears underlined at the upper left side of each matrix. The contextual relationship asks: how do two alternatives compare on the basis of satisfying the requirement imposed by the governing element?

Performance	A	B	C	Priority Vector	
A	1	1/5	1/7	.0691	C.I. = 0.06
B	5	1	1/4	.2437	λ_{max} = 3.12
C	7	4	1	.6870	C.R. = 0.10

Cost	A	B	C	Priority Vector	
A	1	4	5	.6833	C.I. = 0.01
B	1/4	1	2	.1998	λ_{max} = 3.02
C	1/5	1/2	1	.1168	C.R. = 0.02

Schedule	A	B	C	Priority Vector	
A	1	3	5	.6369	C.I. = 0.01
B	1/3	1	3	.2582	λ_{max} = 3.03
C	1/5	1/3	1	.1047	C.R. = 0.03

Risk	A	B	C	Priority Vector	
A	1	5	7	.7306	C.I. = 0.03
B	1/5	1	3	.1883	λ_{max} = 3.06
C	1/7	1/3	1	.0809	C.R. = 0.05

Appendix D: Value Assessment Survey

To AIAA SBR Systems Panel Participants

Dear ___________,

I would like to request your assistance in completing the attached value assessment survey. This survey supports a thesis effort within the Operational Sciences Department of the Air Force Institute of Technology. The thesis effort complements work sponsored by the Air Force Space Technology Center.

Your experience with technology development makes your input especially relevant. The insight that you provide will be an important contribution in judging the relative worth of different space systems.

Please take a few minutes to read the instructions and complete the survey. Should you have any problems in completing the survey, I am available to answer questions and can be contacted at the phone number listed below.

Thank you.

John E. Puffenbarger, Capt, USAF
Graduate Student for Space Operations, AFIT

Local Phone Number _______________

Value Assessment Survey

This survey attempts to solicit the values you place on four criteria. These criteria reflect four major concerns that a decision maker typically takes into account in selecting a particular space system. Performance, cost, schedule, and risk comprise the four that you are asked to consider.

Your role is to act as a senior decision maker. You must decide on the relative importance of achieving the best system performance, minimizing the overall system cost, meeting a demanding time schedule for operational capability, and producing a system of low technological risk.

The relative values that you assign will be used as an input to a methodology for assessing trade-offs in space systems. This methodology uses a decision technique called the analytic hierarchy process (AHP) as the mechanism to evaluate alternative systems.

The analytic hierarchy process works through pairwise comparisons. For this reason, the list of criteria are paired to provide the structure for your evaluation. The scale provided in Table 1 specifies the range of values you may use in making your ratings.

To assist you in your effort, Table 2 decomposes performance, cost, schedule, and risk into elements that may influence the degree of importance you attribute to each. These elements help define each of the four criteria.

Another equally important product of this survey is an expanded definition of the four criteria. Space is provided in Table 2 for you to add elements which you feel influenced your rating of specific criteria. These additions should be elements that you believe must be taken into account when judging the worth of a space system. By providing your input, you are expanding the data base used in characterizing the nature of a space system for the decision maker.

The example on the next page provides guidance concerning how to make comparisons. This should help clarify the process. The survey questions, complete with Tables 1 and 2, follow the example. Thank you for your time and effort in completing this survey.

Example: Comparing Performance to Cost

How important is performance compared to cost in selecting a space system to meet mission objectives?

Based on the scale from Table 1 shown on the next page, this rater felt that performance was of strong importance compared to cost. The rater then circled performance and entered the value of 5 in the corresponding space to indicate this intensity of importance.

This rater also felt that maintainability was an important consideration for judging performance in the comparison. Since maintainability was not originally listed as a performance element in Table 2, the rater then entered maintainability as a write-in element in the abbreviated version of Table 2 shown below.

Criteria	Intensity of Importance
1. (Performance) vs Cost	" 5 "

Performance

Survivability
Coverage
Quality
Capacity
Reliability
Timeliness
Availability

"Maintainability"

____

Begin the survey on the next page.

For each of the following pairs of criteria, which is more important and by what degree? Circle the more important of the two factors listed in the criteria column. Place a value for the degree of that importance in the space provided in the intensity column. Base your ratings on the scale from Table 1.

Criteria	Intensity of Importance
1. Performance vs Cost	______
2. Performance vs Schedule	______
3. Performance vs Risk	______
4. Cost vs Schedule	______
5. Cost vs Risk	______
6. Risk vs Schedule	______

Table 1: AHP Comparison Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over the other.
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another.
7	Very strong or demonstrated performance	A criterion is favored very strongly over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values	When compromise is needed.

Table 2: Criteria Considerations

Performance	Cost
Survivability	R and D
Coverage	Replacement
Quality	Deployment
Capacity	Resupply
Reliability	
Timeliness	
Availability	
______________	______________
______________	______________
______________	______________
______________	______________
______________	______________

Schedule	Risk
Earliest completion date	Number of high risk tech issues
Earliest production date	Number of proven technologies
Potential schedule variability	Number of technologies common to other concepts
______________	______________
______________	______________
______________	______________
______________	______________

Appendix E: Value Assessment Survey Responses

This appendix provides the survey responses of the one participant from the systems panel with the best consistency index. These values are used as the basis for weighting the intermediate criteria in the decision hierarchy.

Criteria	Intensity of Importance
1. Performance vs Cost	" 3 "
2. Performance vs Schedule	" 3 "
3. Performance vs Risk	" 1 "
4. Cost vs Schedule	" 4 "
5. Cost vs Risk	" 1 "
6. Risk vs Schedule	" 4 "

AHP COMPARISON SCALE

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over the other.
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another.
7	Very strong or demonstrated performance	A criterion is favored very strongly over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one criterion over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values	When compromise is needed.

The matrix format below expresses the pairwise comparisons using the value assessment survey results from the previous page. This mathematical depiction is conducive to the matrix calculations required by AHP. The outcome is a priority vector for the intermediate criteria level of the decision hierarchy.

The contextual relationship that governs these comparisons asks: how do two criteria compare on the basis of their contribution toward satisfying the objective of obtaining a space-based radar system. Implicit in these comparisons is the desire for the best performance, within the shortest scheduled timeframe, at the lowest cost, and with minimal risk. The overall objective serves as the governing element in these comparisons.

Key: P = Good Performance

S = Schedule with Early IOC

C = Low Cost

R = Low Risk

<u>Objective</u>

	P	C	S	R	Priority Vector	
P	1	3	3	1	.3879	C.I. = 0.06
C	1/3	1	4	1	.2344	λ_{max} = 4.20
S	1/3	1/4	1	1/4	.0816	C.R. = 0.07
R	1	1	4	1	.2959	

Appendix F: AHP BASIC Program

The following BASIC computer program is adapted from Saaty for use in this methodology (30:252). It performs the function of AHP on the levels of the decision hierarchy demonstrated in the space-based radar example. Entry values and intermediate results with their associated priority vectors appear in Appendix C and Appendix E.

```
1000 REM ANALYTIC HIERARCHY PROCESSES:  PRIORITY HIERARCHY
     PROGRAM
1010 DIM A(99),B(30,30),N(99),Y(99),R(20),C(30,30),W(99),
     W2(99),C7(99),Z(99)
1020 FOR I=1 TO 15
1030 READ R(I)
1040 NEXT
1050 DATA 00.0,0.0,0.58,0.9,1.12,1.24,1.32,1.41,1.45
1060 DATA 1.49,1.51,1.48,1.56,1.57,1.59
1070 REM 2ND LEVEL
1080 L=2
1090 PRINT "ENTER THE NUMBER OF FACTORS IN SECOND HIERARCHY
     LEVEL: "
1100 INPUT N1
1110 PRINT "THE HIERARCHY HAS " N1 " FACTORS IN LEVEL 2."
1120 PRINT "IS THIS CORRECT? IF YES TYPE 0, ELSE TYPE 9."
1130 INPUT Y9
1140 IF Y9>5 GOTO 1100
1150 S1=N1
1160 GOSUB 2140
1170 FOR I=1 TO 60: A(I)=W(I): NEXT I
1180 REM T9 = TOTAL RANDOM CONSISTENCY FOR THIS HIERARCHY.
1190 REM T3 = TOTAL CONSISTENCY FOR THIS HIERARCHY.
1200 REM R() = RANDOM CONSISTENCY TABLE.
1210 L=L+1
1220 FOR I=1 TO 20: FOR J=1 TO 20: B(I,J)=0
1230 NEXT J: NEXT I
1240 PRINT: PRINT "HIT ANY KEY TO CONTINUE. ";
1250 INPUT G7$
1260 PRINT: PRINT "ENTER THE NUMBER OF FACTORS IN LEVEL " L
1270 PRINT: PRINT "IF YOU WANT TO STOP HERE, TYPE A 0.  ";
1280 INPUT N2
1290 PRINT: PRINT N2 "? ";
1300 PRINT: PRINT "IF WRONG TYPE A 9, ELSE TYPE 0. ";
```

```
1310 INPUT Y9
1320 IF Y9 > 5 GOTO 1280
1330 IF N2 < 1 GOTO 2110
1340 REM
1350 FOR N6=1 TO N1
1360 PRINT: PRINT "HIT ANY KEY TO CONTINUE.  ";
1370 INPUT G6$: PRINT
1380 PRINT "ENTER # OF FACTORS IN LEVEL "L" RELATED TO
     ELEMENT "N6" ";
1390 PRINT "OF LEVEL "L-1".";
1400 INPUT N3
1410 PRINT "THIS PROGRAM IDENTIFIES THE ELEMENTS IN LEVEL
     "L
1420 PRINT "BY NUMBERING THEM FROM LEFT TO RIGHT."
1430 PRINT "ENTER THE NUMBER OF EACH ELEMENT IN LEVEL "L
1440 PRINT "RELATED TO ELEMENT "N6" OF LEVEL " L-1"."
1450 PRINT
1460 FOR I=1 TO 60: N(I)=0: NEXT I
1470 FOR I=1 TO N3: INPUT; N(I): NEXT I: PRINT
1480 FOR X=1 TO N3
1490 PRINT N(X) "    ";
1500 NEXT X
1510 PRINT
1520 PRINT "IF WRONG TYPE A 9, ELSE TYPE A 0. ";
1530 INPUT Y9
1540 IF Y9>5 THEN 1470
1550 IF N3>1 GOTO 1590
1560 REM ONLY ONE ELEMENT RELATED
1570 B(N(1),N6)=1
1580 GOTO 1700
1590 S1=N3
1600 GOSUB 2140
1610 FOR I = 1 TO 60: Y(I) = W(I)
1620 NEXT I
1630 T3 = T3 + A(N6)*C8
1640 T9 = T9 + A(N6)*R(N3)
1650 PRINT T3,T9
1660 REM ONLY RELATED ELEMENTS HAVE WEIGHTED VALUES
1670 FOR I = 1 TO N3
1680 B(N(I),N6) = Y(I)
1690 NEXT I
1700 NEXT N6
1710 PRINT: PRINT "HIT ANY KEY TO CONTINUE. ";
1720 INPUT G6$: PRINT
1730 PRINT "*** LEVEL "L" WITH RESPECT TO LEVEL "L-1"."
1740 PRINT
1750 PRINT "WEIGHT: ": PRINT
1760 PRINT "         ";
1770 FOR X = 1 TO N1
1780 PRINT USING "##.####"; INT(10000*A(X))/10000;
1790 NEXT X
1800 PRINT: PRINT
1810 FOR I = 1 TO N2
```

```
1820 PRINT I "   ";
1830 FOR J = 1 TO N1
1840 PRINT USING "##.####";INT(10000*B(I,J))/10000;
1850 NEXT J
1860 PRINT
1870 NEXT I
1880 REM COMPOSITE
1890 FOR I = 1 TO N1
1900 FOR J = 1 TO N2
1910 B(J,I) = B(J,I) * A(I)
1920 NEXT J
1930 NEXT I
1940 FOR I = 1 TO N2
1950 S9 = 0
1960 FOR J = 1 TO N1
1970 S9 = S9 + B(I,J)
1980 NEXT J
1990 A(I) = S9
2000 NEXT I
2019 PRINT
2020 PRINT "*** COMPOSITE PRIORITIES FOR LEVEL "L" ***"
2030 PRINT
2040 FOR X = 1 TO N2
2050 PRINT X;
2060 PRINT USING "###.####";INT(A(X)*10000)/10000
2070 NEXT X
2080 N1 = N2
2090 GOTO 1210
2100 REM CONSISTENCY OF HIERARCHY
2110 PRINT
2120 PRINT "THE CONSISTENCY OF THIS HIERARCHY = "
     INT(100*T3/T9)/100
2130 GOTO 3120
2140 PRINT: PRINT "ENTER THE UPPER TRIANGULAR PART OF THE
     MATRIX."
2150 PRINT "DO NOT ENTER THE ELEMENTS ALONG THE MAIN
     DIAGONAL."
2160 PRINT "AFTER EACH QUESTION MARK, ENTER ONE ELEMENT OF
     THE ROW."
2170 PRINT "ELEMENTS LIKE 1/3 SHOULD BE ENTERED AS -3."
2180 PRINT
2190 FOR I = 1 TO S1 - 1
2200 PRINT
2210 PRINT "ROW "I":"
2200 FOR J = I + 1 TO S1
2230 INPUT;C(I,J)
2240 NEXT J
2250 PRINT
2260 FOR J = I+1 TO S1
2270 PRINT C(I,J);
2280 PRINT " "
2290 NEXT J
2300 PRINT
```

```
2310 PRINT "IF WRONG TYPE A 9 ELSE TYPE A 0. ";
2320 INPUT Y9
2330 IF Y9 > 5 GOTO 2210
2340 FOR J = I + 1 TO S1
2350 IF C(I,J) > = 0 GOTO 2370
2360 C(I,J) = -(1/C(I,J))
2370 C(J,I) = 1/C(I,J)
2380 NEXT J
2390 NEXT I
2400 FOR I = 1 TO S1
2410 C(I,I) = 1
2420 NEXT I
2430 REM FIND INITIAL WEIGHT
2440 T4 = 0
2450 FOR I = 1 TO S1
2460 S = 0
2470 FOR J = 1 TO S1
2480 S = S + C(I,J)
2490 NEXT J
2500 W2(I) = S
2510 T4 = T4 + S
2520 NEXT I
2530 FOR I = 1 TO S1
2540 W2(I) = W2(I)/ T4
2550 NEXT I
2560 REM
2570 K = 0
2580 T4 = 0
2590 K = K + 1
2600 FOR I = 1 TO S1
2610 S = 0
2620 FOR J = 1 TO S1
2630 S = S + C(I,J) * W2(J)
2640 NEXT J
2650 W(I) = S
2660 T4 = T4 + S
2670 NEXT I
2680 D = 0
2690 FOR I = 1 TO S1
2700 W(I) = W(I) / T4
2710 D = D + ABS(W(I) - W2(I))
2720 NEXT I
2730 IF K > 10000 GOTO 2770
2740 IF K < .0001 GOTO 2770
2750 FOR I = 1 TO 60:W2(I) = W(I): NEXT I
2760 GOTO 2580
2770 PRINT
2780 PRINT "LEVEL ";L;" ELEMENT "N6: PRINT
2790 PRINT "INPUT MATRIX": PRINT
2800 FOR I + 1 TO S1
2810 C(I,I) = 1
2820 FOR J = 1 TO S1
2830 PRINT USING "###.####";INT(C(I,J)*1000)/1000;
```

```
2840 NEXT J
2850 PRINT
2860 NEXT I
2870 REM
2880 FOR I = 1 TO S1
2890 S = 0
2900 FOR J = 1 TO S1
2910 S = S + C(I,J) * W(J)
2920 NEXT J
2930 C7(I) = S
2940 NEXT I
2950 S = 0
2960 FOR I = 1 TO S1
2970 S = S + C7(I) / W(I)
2980 NEXT I
2990 Y5 = S/S1
3000 C8 = (Y5 - S1) / (S1 -1)
3010 PRINT: PRINT"WEIGHTS"
3020 PRINT
3030 FOR I = 1 TO S1
3040 PRINT USING "###.####";INT(W(I) * 10000) / 10000
3050 NEXT I
3060 PRINT
3070 PRINT "LAMBDA(MAX) = " INT(Y5*100)/100
3080 PRINT
3090 PRINT "C.I. = " INT(C8*100)/100
3100 PRINT
3110 RETURN
3120 END
```

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ABSTRACT: A methodology is developed to aid a decision maker in assessing the technology trade-offs for space system concepts. A review of systems engineering and the tools of operations research shows that the analytic hierarchy process provides a suitable basis for this methodology.

The possible concept options that fall under the overall space-based radar concept are representative of the multiple trade-offs inherent in planning for future space systems. Many of the technology issues appropriate to space-based radar concepts are presented to establish a foundation for the methodology.

The proposed methodology exposes the three phases of the analytic hierarchy process and how they interact to provide an overall priority for a selected number of concept options. Particular emphasis is placed on the division of the decision process according to a decision hierarchy and a support hierarchy. A key feature of such an approach is its compatibility with the format and terminology of the Military Space Systems Technology Plan developed by the Air Force Space Technology Center.

Three concept options serve as representative systems to demonstrate the feasibility of the methodology. Recommendations on how to expand upon the model follow this example. Concluding remarks suggest a decision support system based on this methodology using the AFSTC Data Base Management System to enhance the MSSTP decision process.

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